Low-Swirl Flame Stabilization Method for Lean Premixed Turbulent Flames and Its Adaptation to Heating and Power Equipment

Robert K. Cheng
Senior Scientist
Leader, Combustion Technologies Group
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory

Presentation at ABMA Mid-Winter Meeting Jan. 18, 2004

Acknowledgement

- ***Sponsors***
  - DOE-Basic Energy Sciences, Chemical Sciences
  - DOE-Basic Energy Sciences, Laboratory Technology Research
  - California Institute of Energy Efficiency/SoCalGas
  - DOE-EERE, Office of Industrial Technology
  - DOE-EERE, Distributed Energy Resources
- ***Collaborators***
  - D. Yegian, D. Littlejohn, G. Hubbard, K. Hom & I. Shepherd (LBNL)
  - J. Rafter & C. Taylor (Maxon), K. O. Smith (Solar Turbines)
    C. Castildini (CMC Eng.), C. Benson (TIAX),
    M. Miyasato, V. McDonell, R. Hack & G. S. Samuelsen (UC Irvine),
    H. Rieher (Industrial Combustion)

Modes of Gaseous Combustion

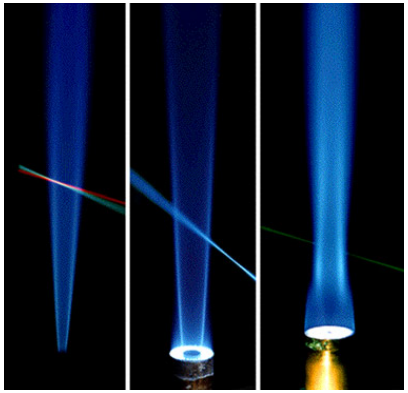
Diffusion Flame
controlled by mixing

Partially Premixed Flame
two reaction zones

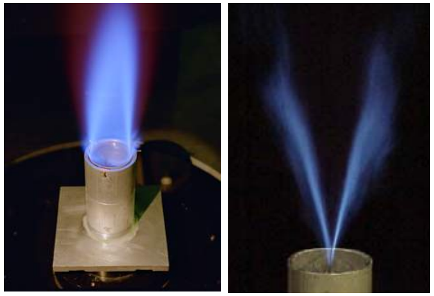
Lean Premixed Flame
wave-like flame front

Turbulent Combustion as a Fundamental Research Problem

- No unified theory due to differences in the predominant physical processes of non-premixed and premixed flames

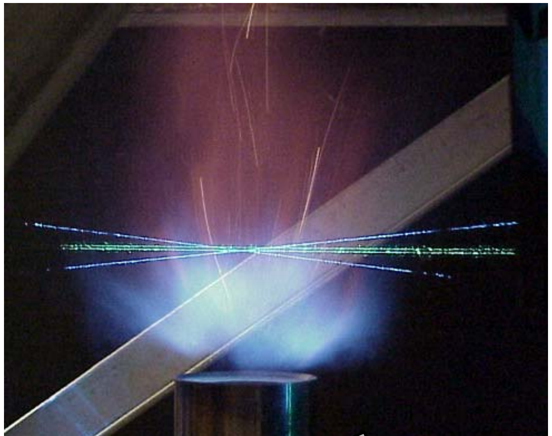


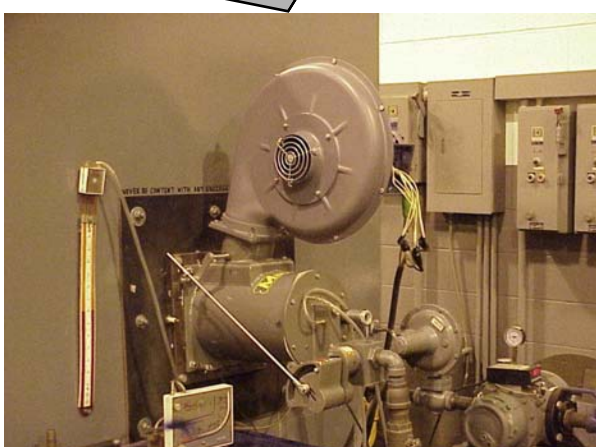
- ***Non-premixed (diffusion) flames***
  - Turbulent and molecular mixing control combustion rates, efficiency and pollutant formation
    - Reactions occur at stoichiometric contours passive to turbulence
    - Combustion products diffuse into fuel and oxidizer streams
  - Reaction rate models expressed in terms of species concentrations



- ***Premixed flames***
  - Self propagating flame front separate reactants from products
  - Flame front exhibits wave behavior and generates significant feedback to turbulent field through the pressure field
  - Reaction rate models expressed in terms of flame speed

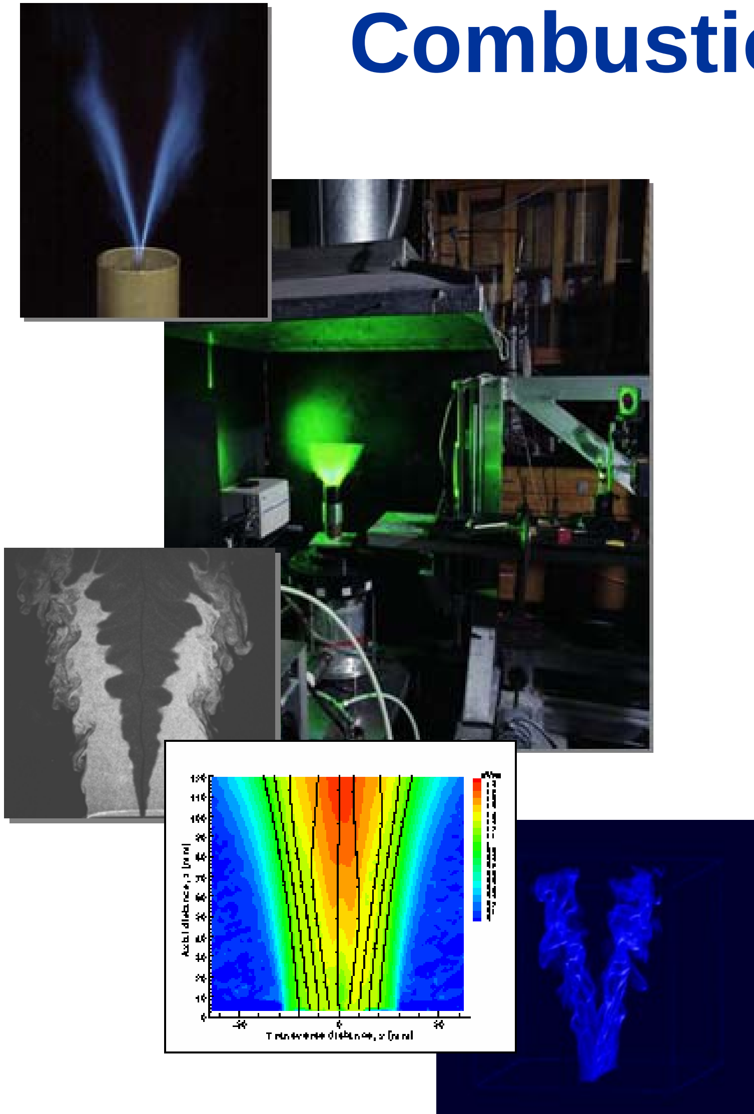
LBNL's Basic Research Focuses on Gaseous Premixed Turbulent Flames





- Theoretical Interest
  - Turbulence intensity and sizes of eddies control burning rate, power density and flame stability
- Technological Interest
  - Reduction of NOx emissions through lean combustion
- Programmatic objectives
  - Elucidate turbulence/flame interactions processes
  - Build an experimental foundation to advance combustion theories & models
  - Transfer scientific knowledge to practical use

LBNL’s Basic Research Emphasizes Combustion Fluid Mechanics



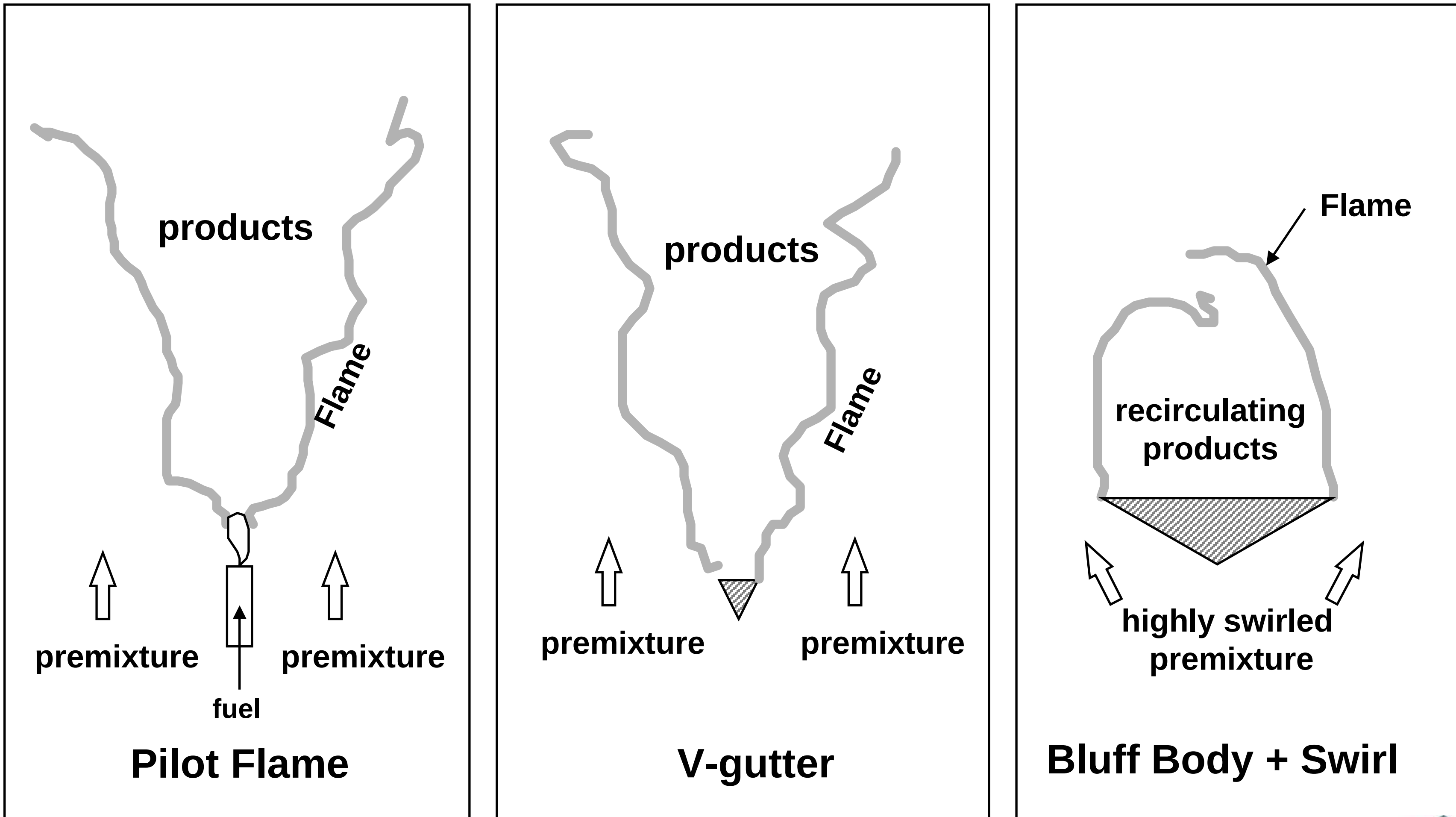
- Approach: Laboratory investigations and theoretical development to quantify flame turbulence interactions
  - “clean” experiments to reveal and isolate various processes
  - systematic variation of combustion and turbulence parameters
- Goal: Support the development of computational tools suitable for the design of advanced combustion systems

Addressing Problems Relevant to Lean Premixed Combustion Systems

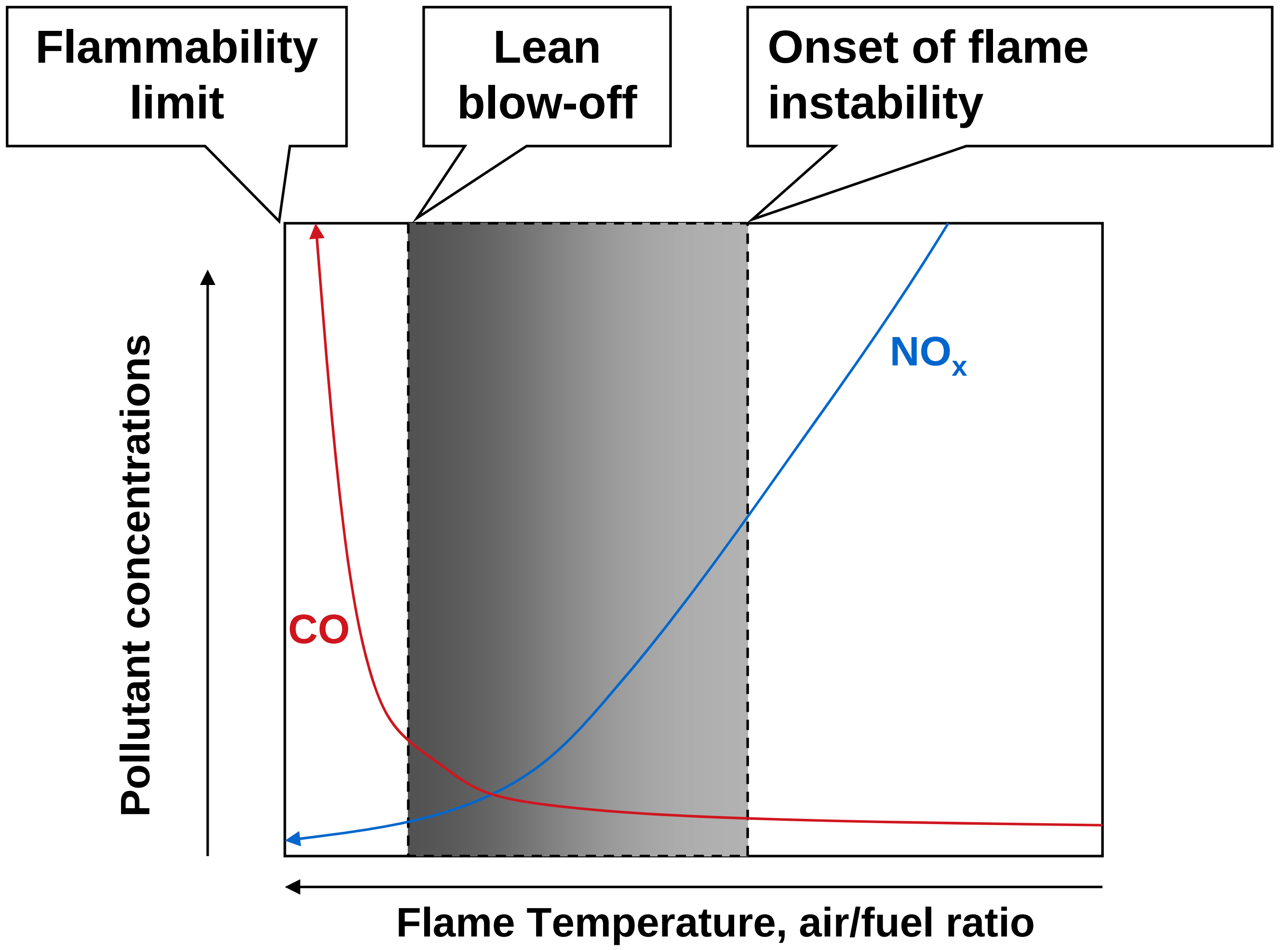
- Incomplete knowledge on flame behavior
  - fast burning, compact & intense flames
  - turbulence effects on emissions
  - flame interaction with combustion chambers
- Flame holders dictates performance
  - restrict operating range (5:1 turn-down vs. 10:1 for non-premixed systems)
  - impact fuel flexibility, costs, & durability
- Flame generated flow dynamics
  - noise and vibrations
  - flash-back and blow-out hazards

Conventional Flame Holders

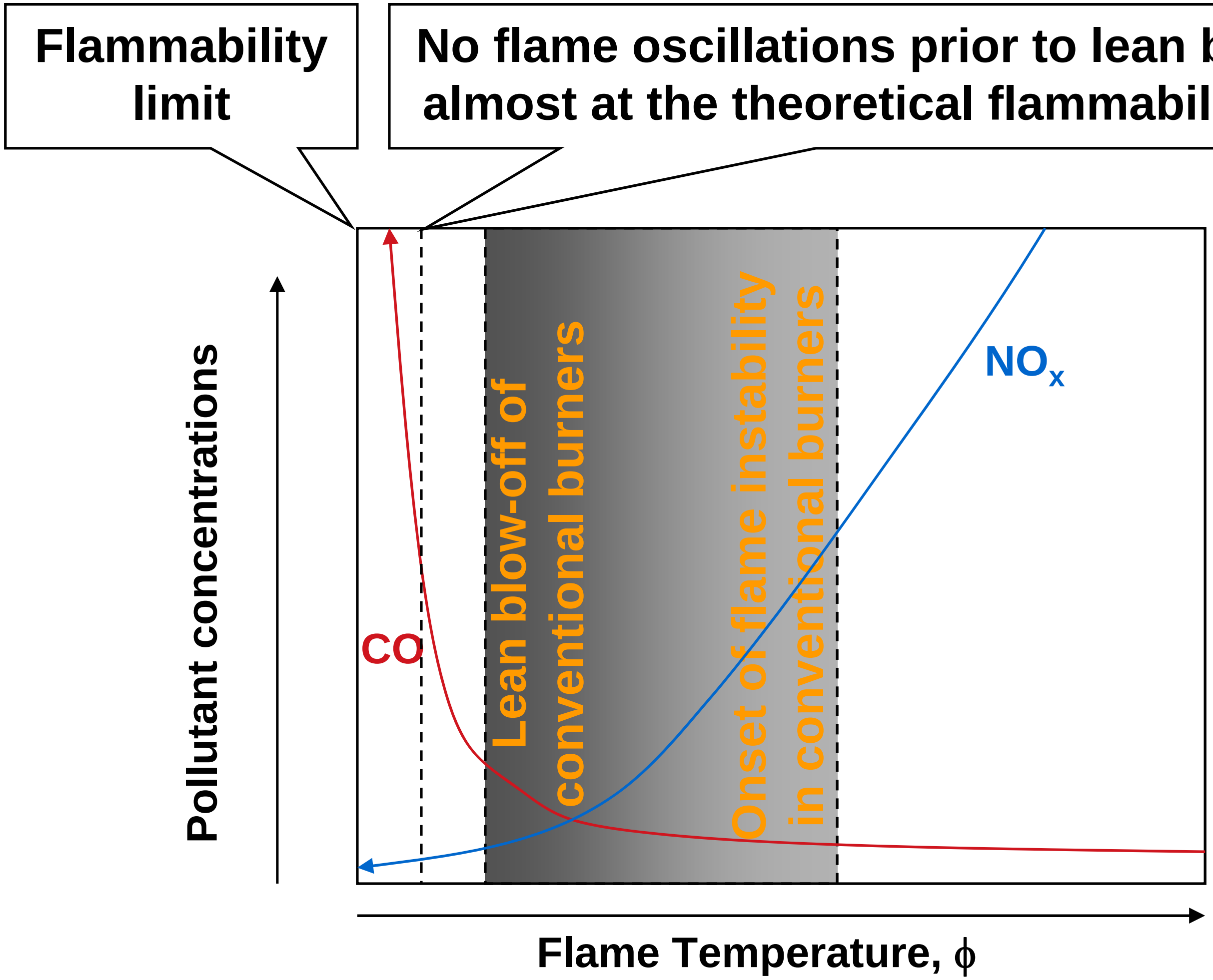
- Based on the theoretical principle of continuous ignition source provided by a ***pilot flame*** or in the hot ***recirculation zone*** behind the stabilizer



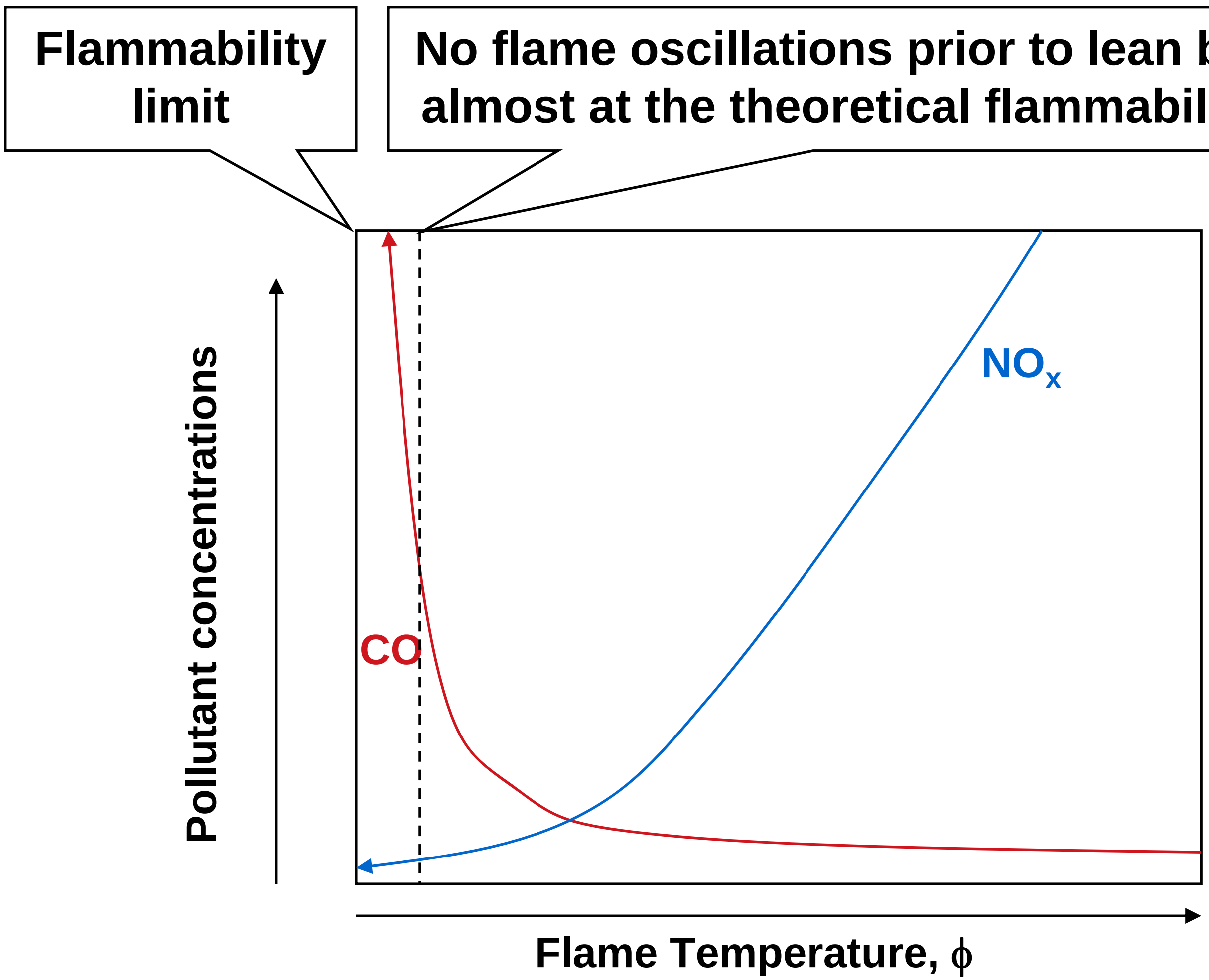
Lean Blow-off and Flame Instabilities Associated With Different Flame Holders Are Barriers to Reaching Low-Emissions



Low-swirl Combustion Exploits Aerodynamics to Overcome the Barriers to Attaining Low-Emissions



Low-swirl Combustion Exploits Aerodynamics to Overcome the Barriers to Attaining Low-Emissions

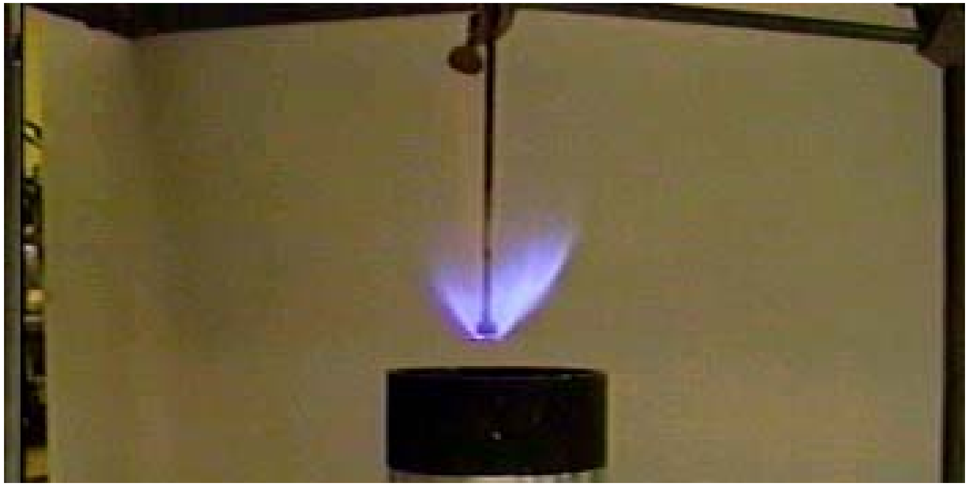


Premixed Flames Stabilized by Low Swirl

- ***Novel concept discovered in 1991 at LBNL***
  - ***Defies recirculation theory on flame stabilization***
- ***Scientific Interest***
  - Scientific background lacking for low-swirl flows
  - Challenging modeling problem
  - Excellent laboratory research tool
- ***Technological Interest***
  - Capability to support ultra-lean flames
  - Simple design
  - Patent awarded 1998

Flame Holders Were Considered Essential to Anchor Lean Premixed Flames

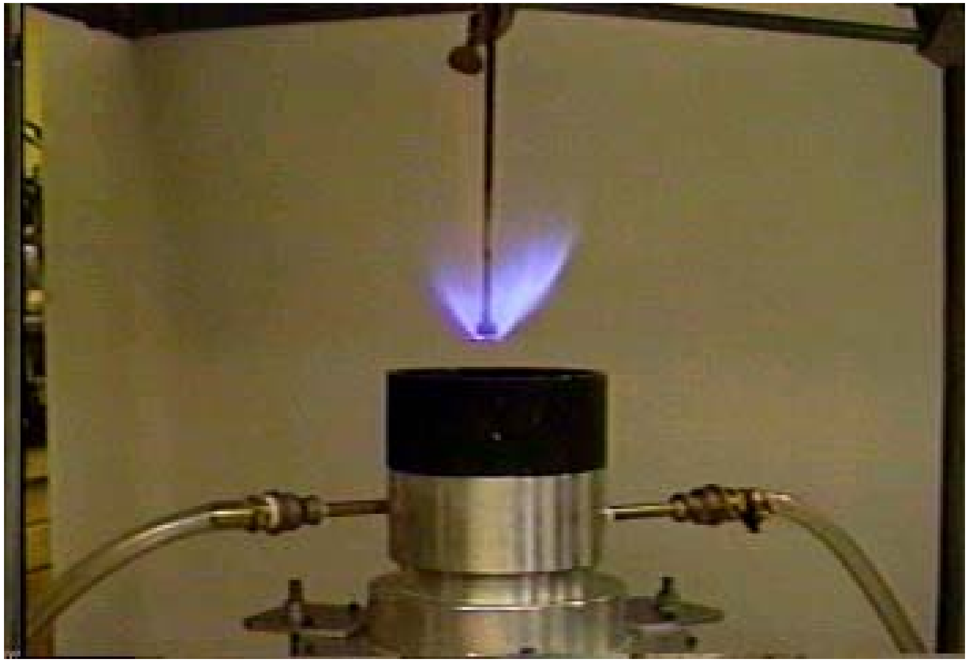
- Premixed flames requires a physical stabilizer so that it can anchor. This flame is stabilized by a bluff body of about 1 cm diameter



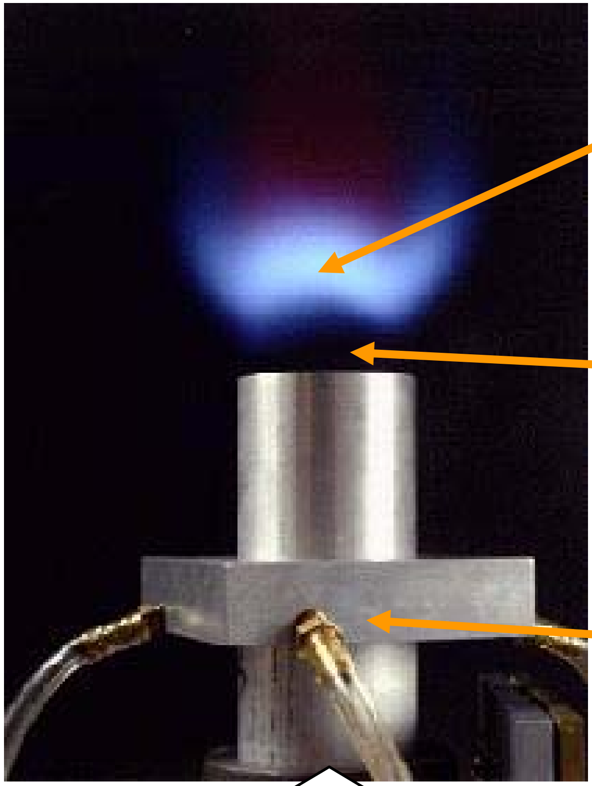
Reactants

Low-Swirl Eliminates the Need for a Flame Holder

- By introducing a very small amount of swirl air (swirl number S ≈ 0.6), this video shows that the flame can self propagate without the bluff body



Low-Swirl Flame Stabilization Exploits Propagating Nature of Premixed Flames



Fuel/Air mixture

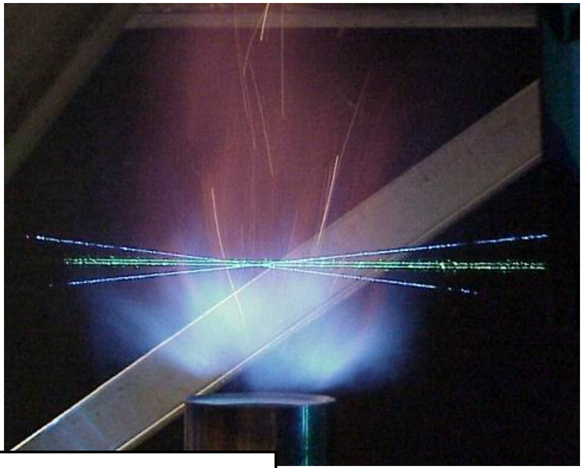
Propagating against the divergent flow, the flame settles where the local velocity equals the flame speed

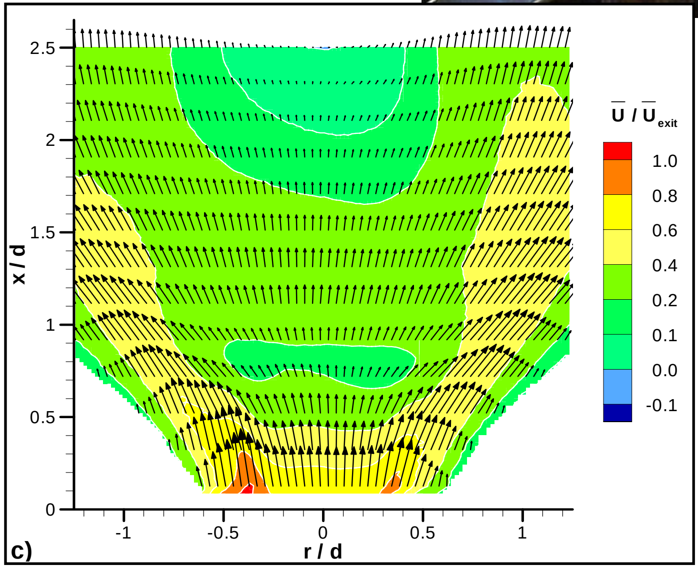
Flow divergence (generated by low-swirl) above the burner tube is the key element for flame stabilization

Small air jets swirl the perimeter of the fuel/air mixture but leave the center core flow undisturbed

Laser Diagnostics Characterized Flame Stabilization Mechanism

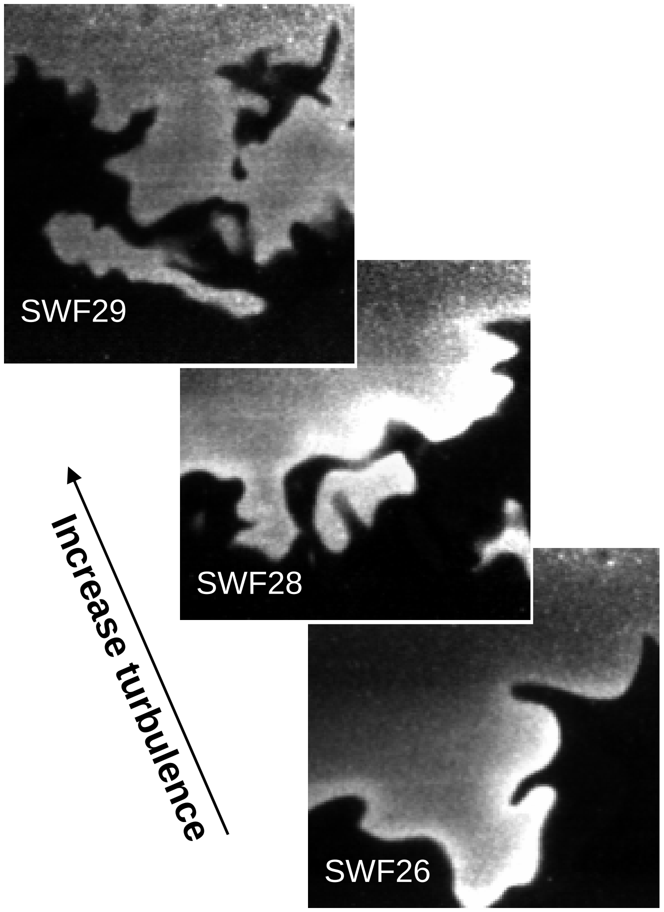
- Flow divergence provides a much more stable mechanism for lean flames than high swirl flows or flame holders
- Flame brush propagates at turbulent flame speed that increases linearly with turbulence intensity
  - flashback conditions predictable
- Swirl intensity controls flame lift off position





Scientific Studies Using Jet-LSBs

- Exploiting LSB's capability to supports premixed turbulent flames under a wide range of turbulence and mixture conditions has helped to resolve key scientific problems
  - Investigate evolving turbulent flame structures from low to intense turbulence
  - Verify new theory on classification of premixed turbulent flames
  - Relate turbulent flame speed to combustion intensity

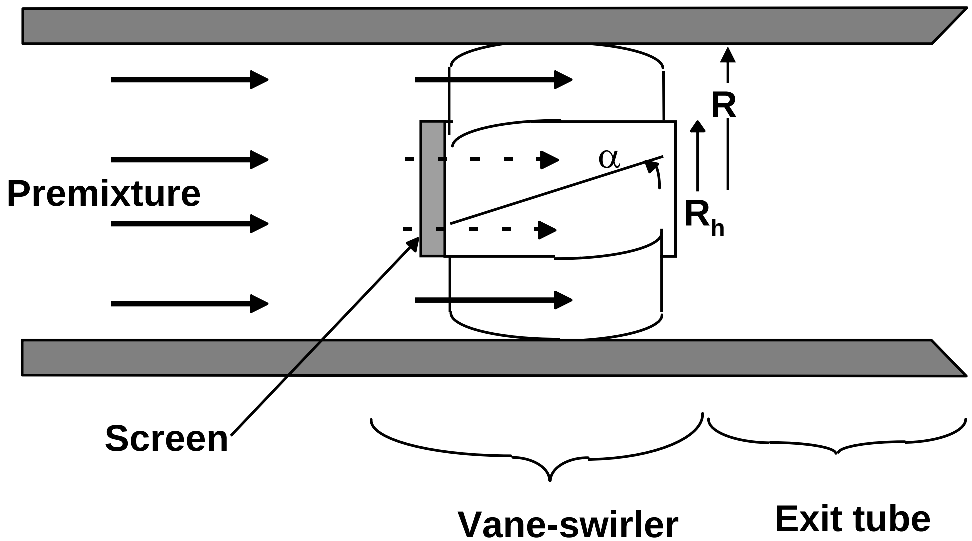


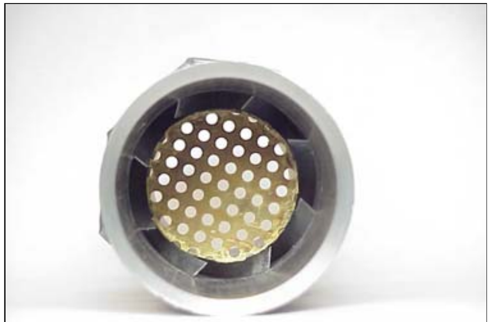
These images of OH fluorescence obtained by laser diagnostics are the data for studying combustion intensities and flame structures

First Technology Transfer Project Supported by DOE-LTR (1994-1997)

- ***CRADA with Teledyne-Laars***
- ***Adaptation to pool heaters***
  - Design and test LSBs that meets the operational requirements of 15 KW to 100 KW units
  - Sizes similar to laboratory LSBs
  - Non-modulated systems, no turndown requirement
- ***Issues***
  - ***need simpler design requiring only one flow supply (no jets)***
  - firing sideways or downwards to attain > 85% efficient
  - stable inside chamber
  - cannot compromise on energy efficiency
  - cost must be lower than Alzeta burner ($100/per unit)

Vane-Swirler Developed for LSB

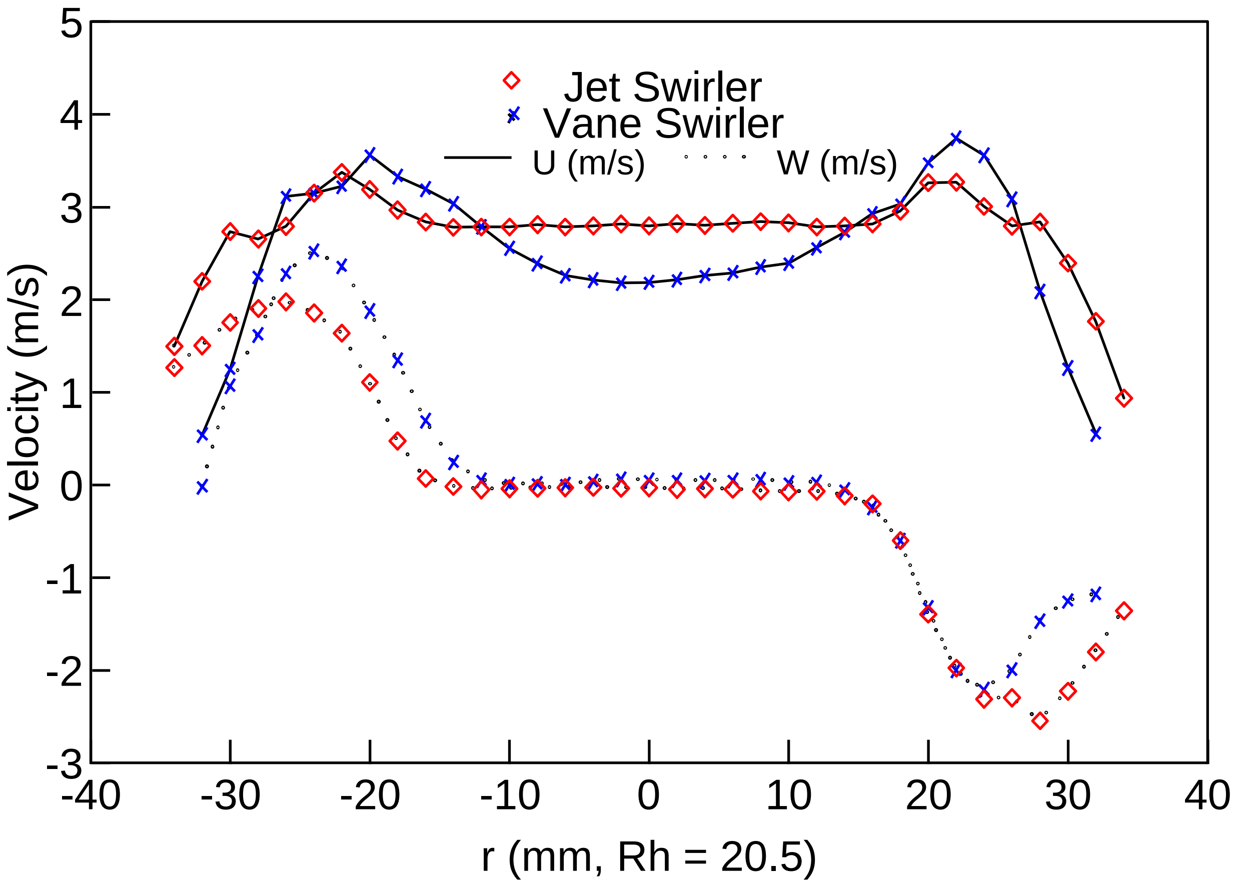




Top view of patented vane-swirler

- ***New design fundamentally different than that of conventional vane-swirler***
  - Open center channel allows a portion of flow to bypass swirl vanes
  - Angled guide vanes induce swirling motion in annulus
  - Screen balances pressure drops between swirl and center channel
- ***Patent awarded in 1999***

Development of Vane-Swirler Relied on Laser Diagnostics



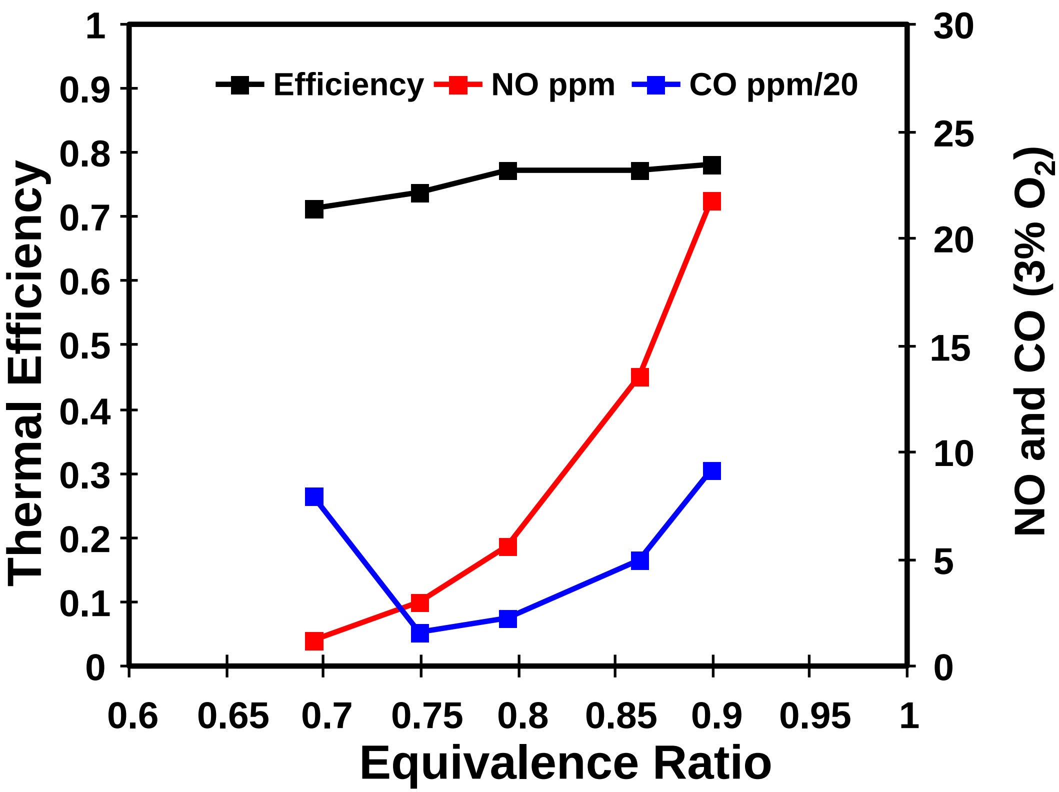
- Varied screens blockage, vane angle, and inner tube diameter
- Measured mean velocity profiles and compare with profiles of jet-swirler

Vane-Swirler for LSB Can Be Made From Simple and Low-Cost Materials

This burner is made of PVC and plastic to showcase the uniqueness of LSB

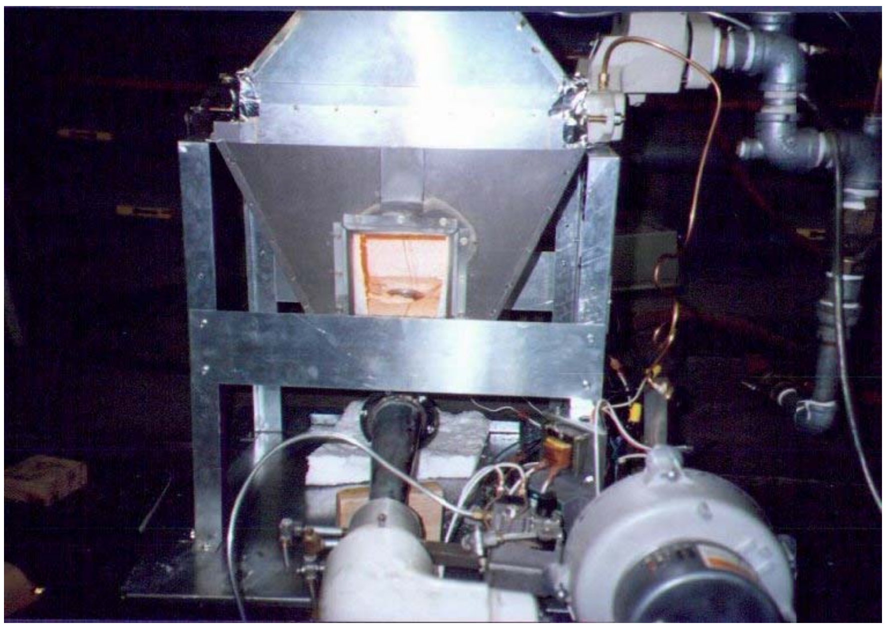
- Vane-LSB produces the same shape as Jet-LSB
- Lifted flame does not transfer heat to burner throat
- Estimated fabrication cost for pool heaters < $10/unit

Pool Heater with Low-Swirl Burner Achieved < 10 ppm NO_x



- Flame remains stable inside chamber
- No compromise on thermal efficiency
- CO can be further reduced
- LSB compatible with ignition and control systems of current products

Technical Success But No LSB Product!



Prototype with a 75 kW LSB (250,000 BTU/hr)

- Clean and highly efficient pool heaters represent a small sector of T-L product line
- Growing market in Southwest regions (e.g. AZ) has no emission regulations
- Market needs in California can be met by out-sourcing to burner suppliers (Alzeta)
- R&D dollars re-directed to updating product appearance (signature look) and improving ease and convenience of operation (remote control)

Scaling to Industrial Sizes (CIEE 1997-2001, DOE-OIT 2000-present)

- ***Established adaptability to process heat and boilers***
  - Targeting single burner ranging from 0.5 MW to 20 MW
  - Starting at a minimum of 6X scale up from LSB for pool heaters
- ***Obtained scaling information***
  - Lacking scientific background information for low-swirl flows
  - Theory on turbulent flame speed predicts flame blowout
  - Possible trade-off and/or compromise between two scaling approaches
    - increasing flow velocity versus increasing burner diameter

Learn From Equipment Manufacturers

- ***Presentations at American Flame Research Committee meetings***
- ***Discussion with R&D engineers and managers***
  - Site visits and demonstrations
- ***Outreach and publicity***
  - LBNL Technology Transfer booth at trade shows
  - Appearance in “Your New Home” on Discovery channel

Key Scaling Questions

- ***What are the critical design components of the LSB?***
  - Size of center channel?
  - Exit tube length?
  - Vane angle?
  - Vane length?
  - Screen placement position?
  - Homogeneity of mixture?
- ***How high we can push the throughput?***
  - Do we need to adjust swirl to accommodate flame shift?
  - Will the flame blows out as in other burners?
  - How does the aerodynamic flowfield evolve at high velocities?
- ***How much can we increase the burner diameter?***
  - Will increase burner diameter affect flame stability range and thus swirl requirement?
- ***Is there a convenient scaling rule that engineers can use?***

Critical First Step – Quantify Swirl Rates By New Swirl Numbers Derivations

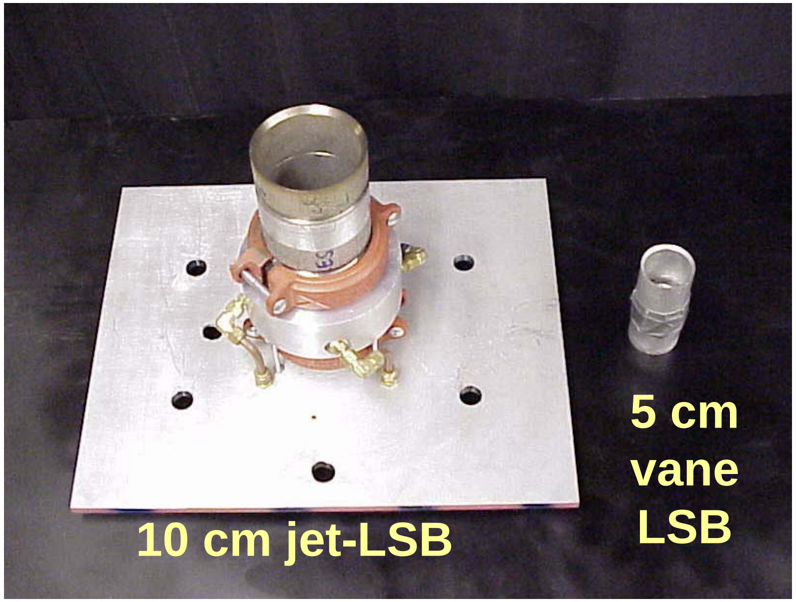
- **For air-jet swirler S defined in terms of flow rates**

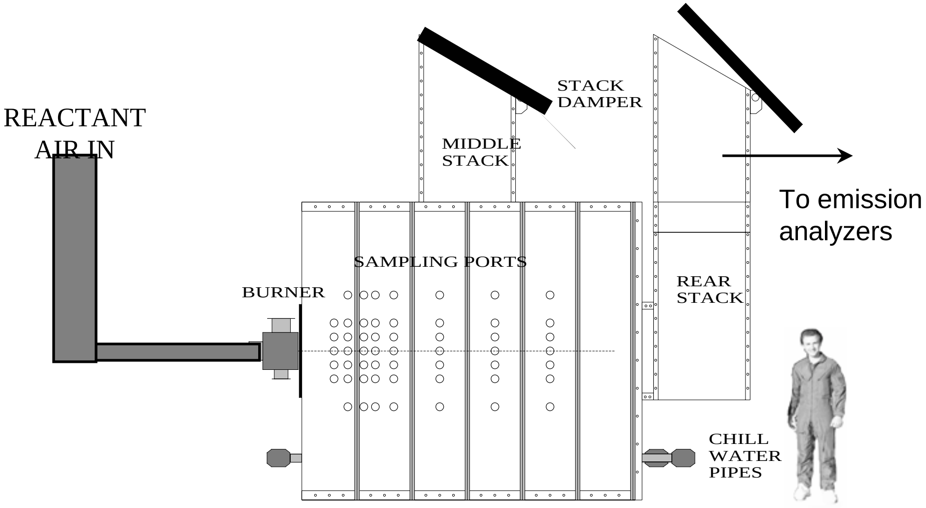
$$S = \frac{\pi R^2}{4\pi R_j^2} \frac{\dot{m}_j^2 \cos\alpha}{\left(\dot{m}_i + \dot{m}_j\right)^2}$$

- **For vane-swirler, momentum integrations gives an equation in terms of flow velocities**
  - not a convenient form for engineering application

$$S_v = \frac{2}{3} \tan\alpha \frac{1 - \left(R_c / R\right)^3}{1 + \left(R_c / R\right)^2 \left(\left(U_c / U_a\right)^2 - 1\right)}$$

Obtaining Scaling Information Through Laboratory Studies

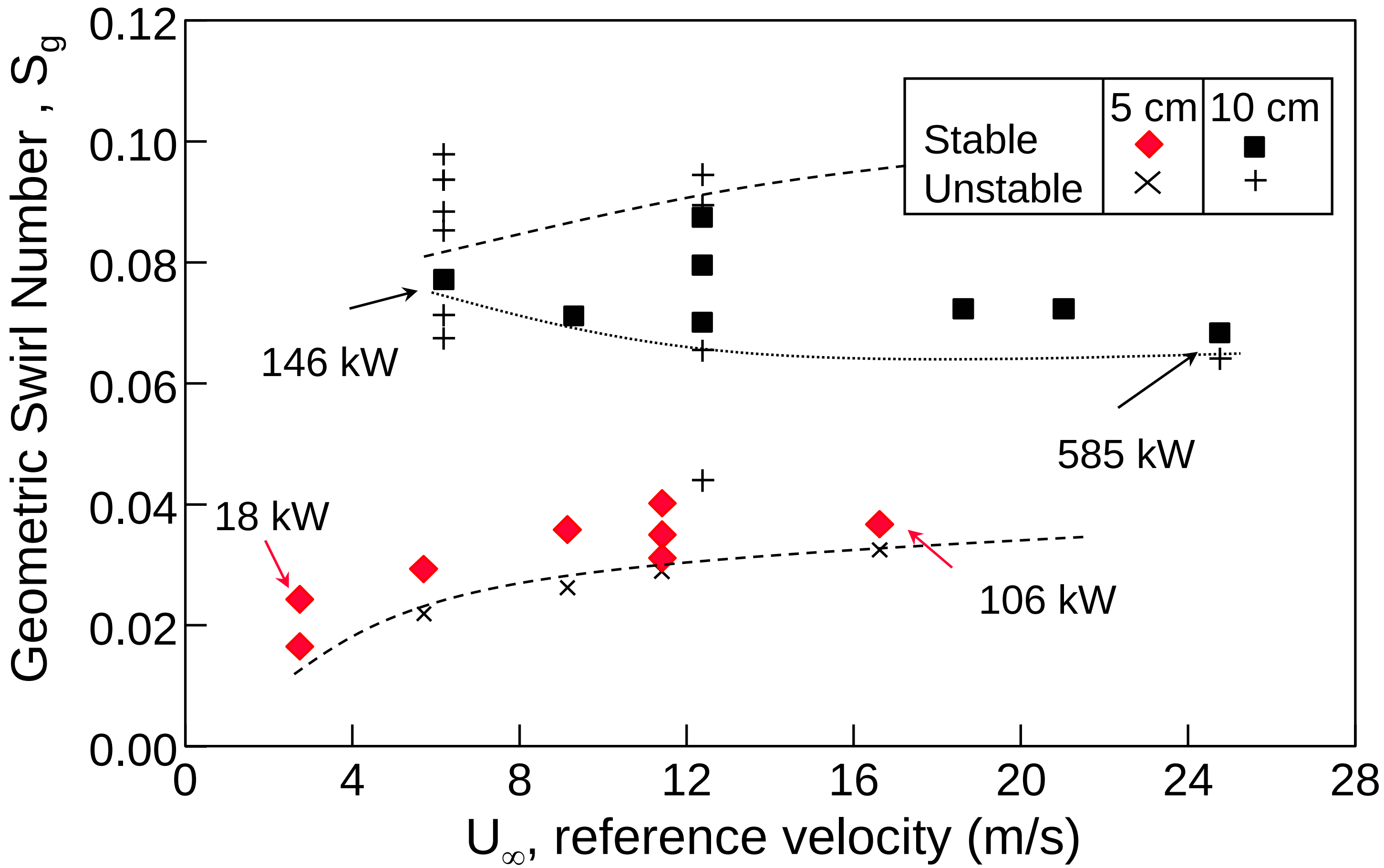




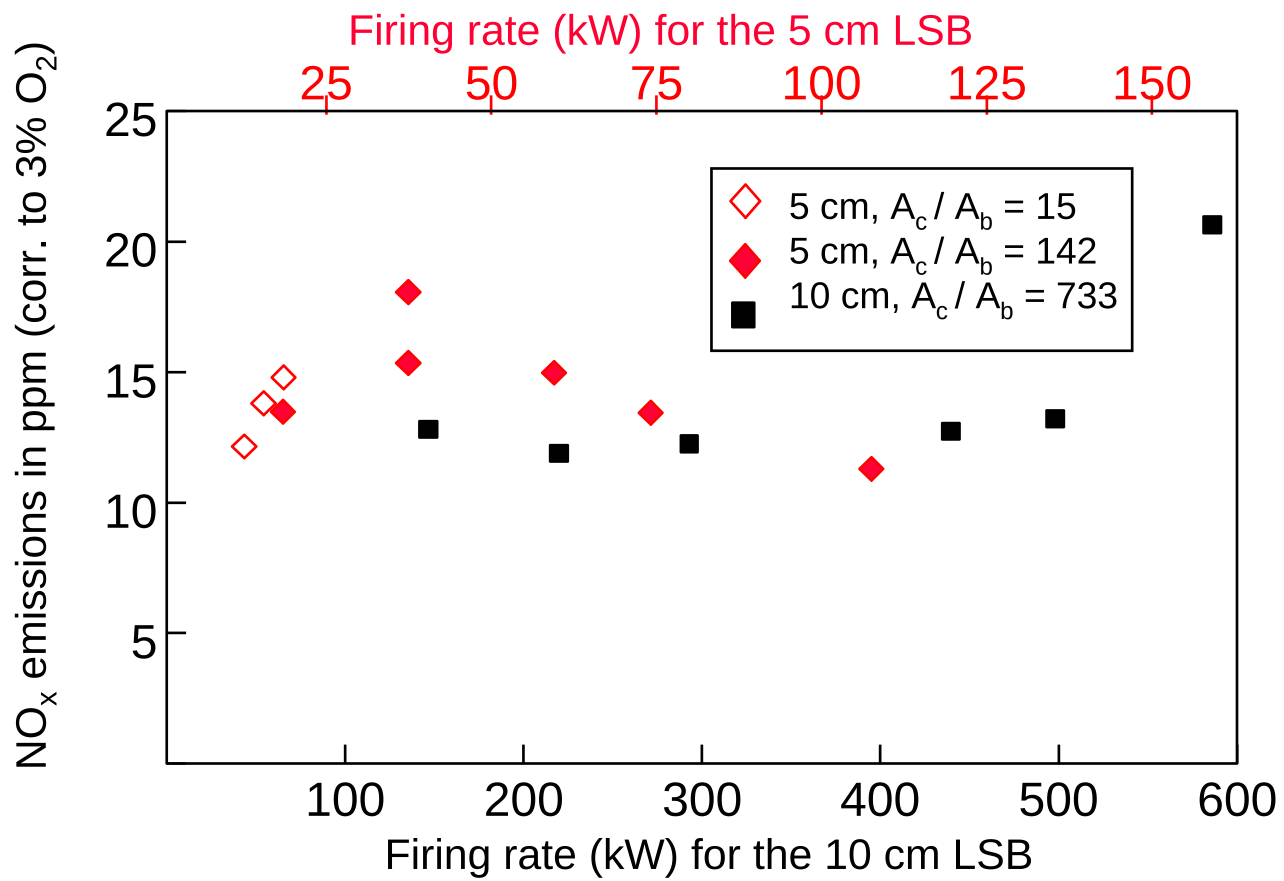
- Comparing LSBs of different sizes
- 10 cm jet-LSB has dimensions twice those of 5 cm jet-LSB
  - Tested at furnace simulator 150 to 600 kW ($6 < U < 25$ m/s)
  - Determine swirl number, lean blow off and emissions
  - Compare results with 5 cm jet-LSB

Swirl Requirement Independent of Load

- **Vane-swirler does not require adjustments for load change**
- **Swirl rate subscribes to residence time scaling**



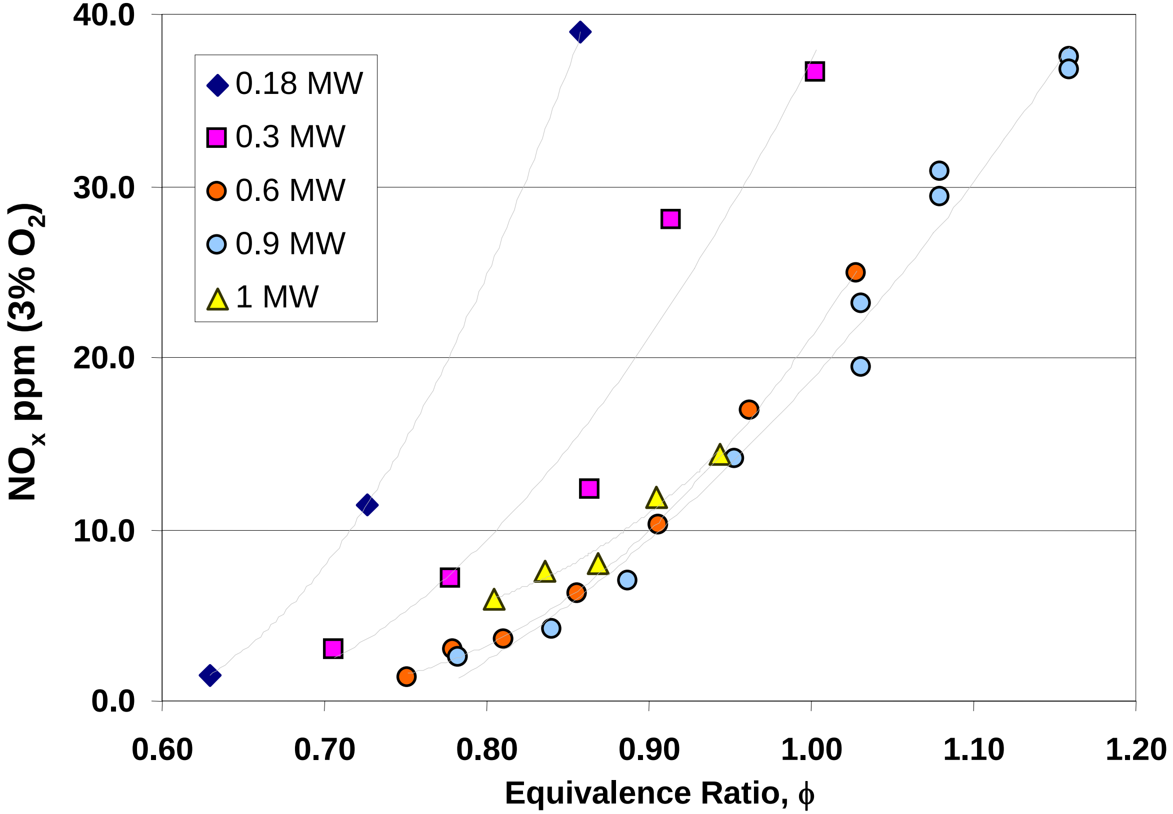
NO_x Emissions Independent of Burner Size and Velocity



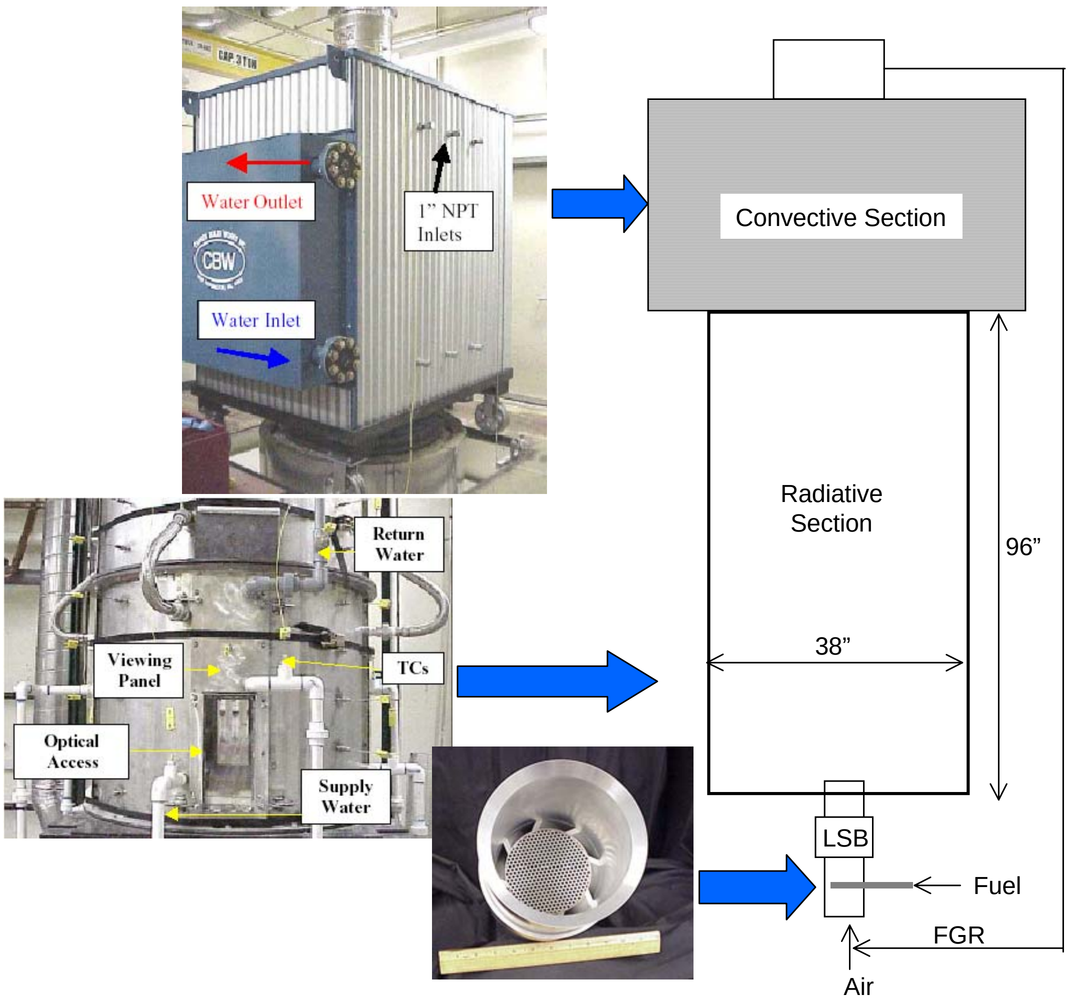
≈

Continue Development of Vane-Swirler

- Larger 7.7 cm LSB reached 1 MW in furnace simulator
- NO_x < 10 ppm, CO < 25 ppm and UHC undetectable



Further Scale-up to 12.7 cm and Investigated Effects of Vane-design



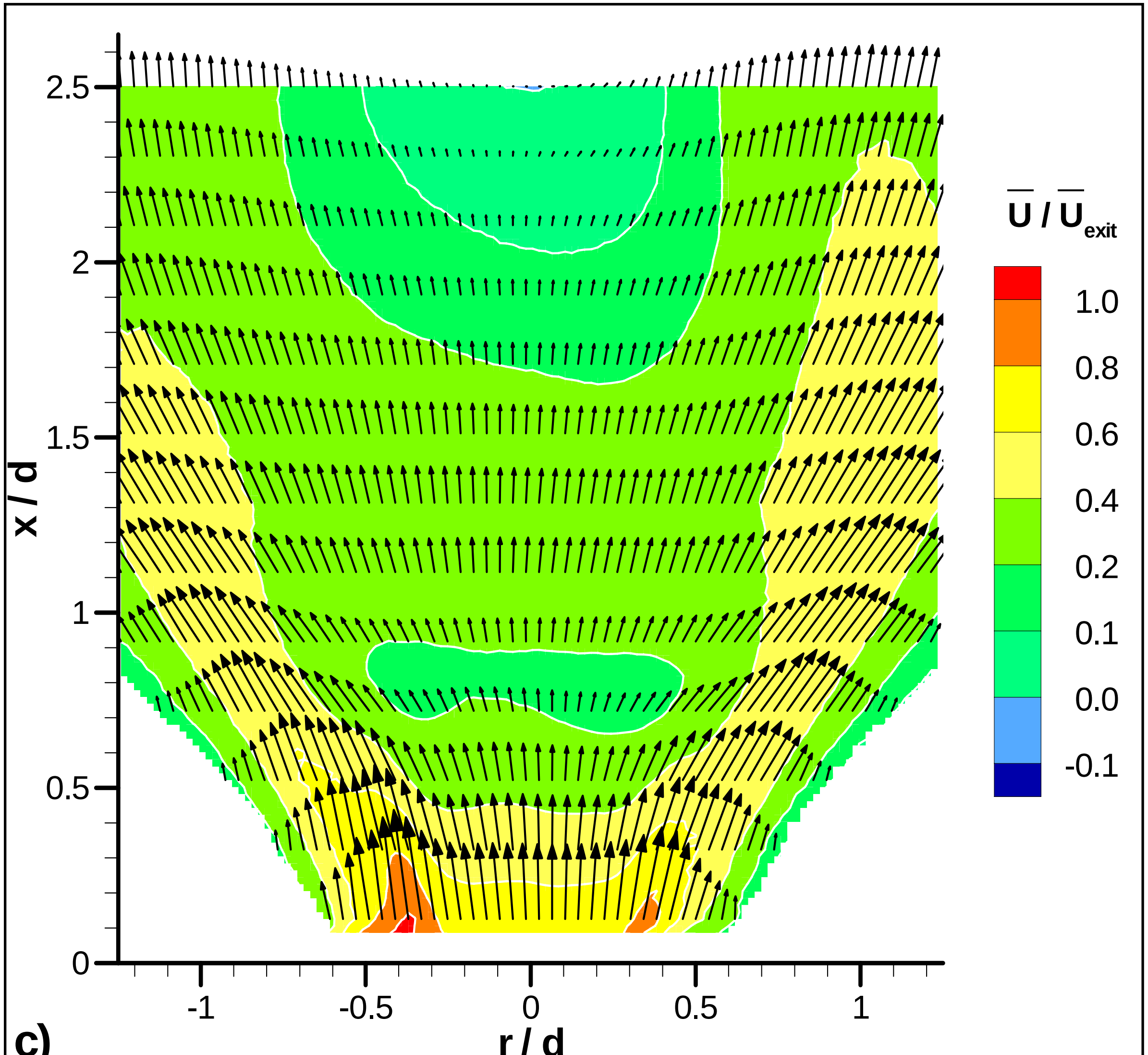
12.7 cm LSB fitted in boiler simulator at UC Irvine

- 12.7 cm LSB with four vane types
  - curved vanes $\alpha = 45^o$
  - curved vanes $\alpha = 37.5^o$
  - straight vanes $\alpha = 37.5^o$ short
  - straight vanes $\alpha = 37.5^o$ long
- For $0.7 < \phi < 0.9$, 0.6 to 1.3 MW emissions and burner performance independence of vane design & number of vanes

Laser Studies Provided Important Scientific Clues for LSB's Robust Performance

- Analyses drawn upon the theories on
  - Turbulence scaling, production, and dissipation
  - Flame temperature, flame speed and reaction chemistry
  - Combustion aerodynamics
- Found LSB generates self-similar flowfield
  - Flow divergence constant in non-dimensional space
  - No flame shift due to linear scaling of turbulence intensity and flame speed
- Knowledge essential for identifying, prioritizing and resolving operational issues
  - Placement of flame ignitor
  - Protocol to maintain flame stability during turndown and turnup
  - Premixing requirement
  - Flow conditioning upstream

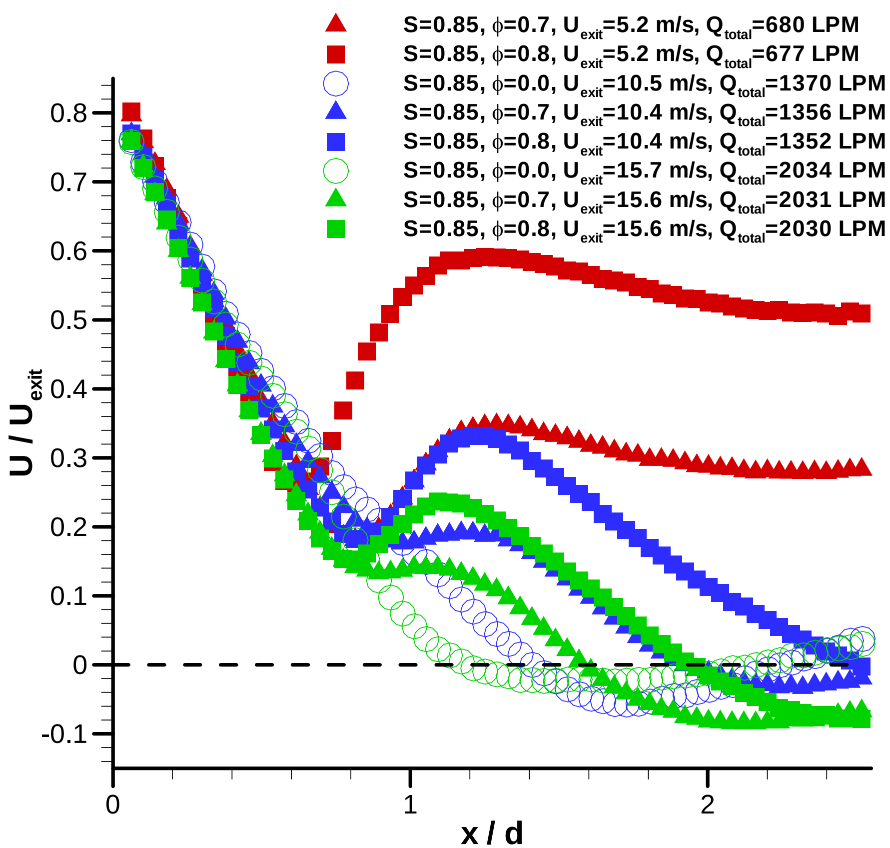
Velocity Vectors of LSB Show How It Prevents Flash-back

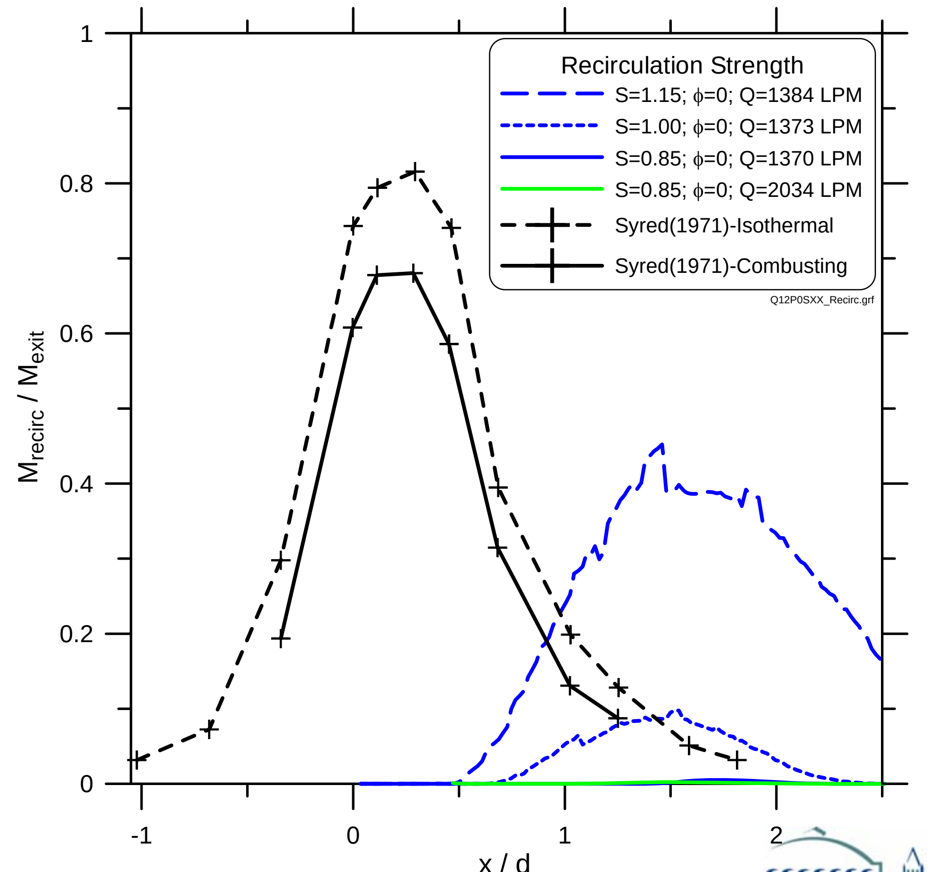


- Particle Image Velocimetry (PIV) measurements show relatively uniform high inflow velocities with no back-flow

Found Self-Similarity Flowfield and Weak Downstream Recirculation

- Self-similarity explains why flame does not shift with load
- Weak recirculation shows it to be irrelevant





Refinement of Swirl Number Definition for Combustion Engineers

$$S = \frac{2}{3}\tan\alpha \frac{1-R^3}{1-R^2+[m^2(1/R^2-1)^2]R^2}$$

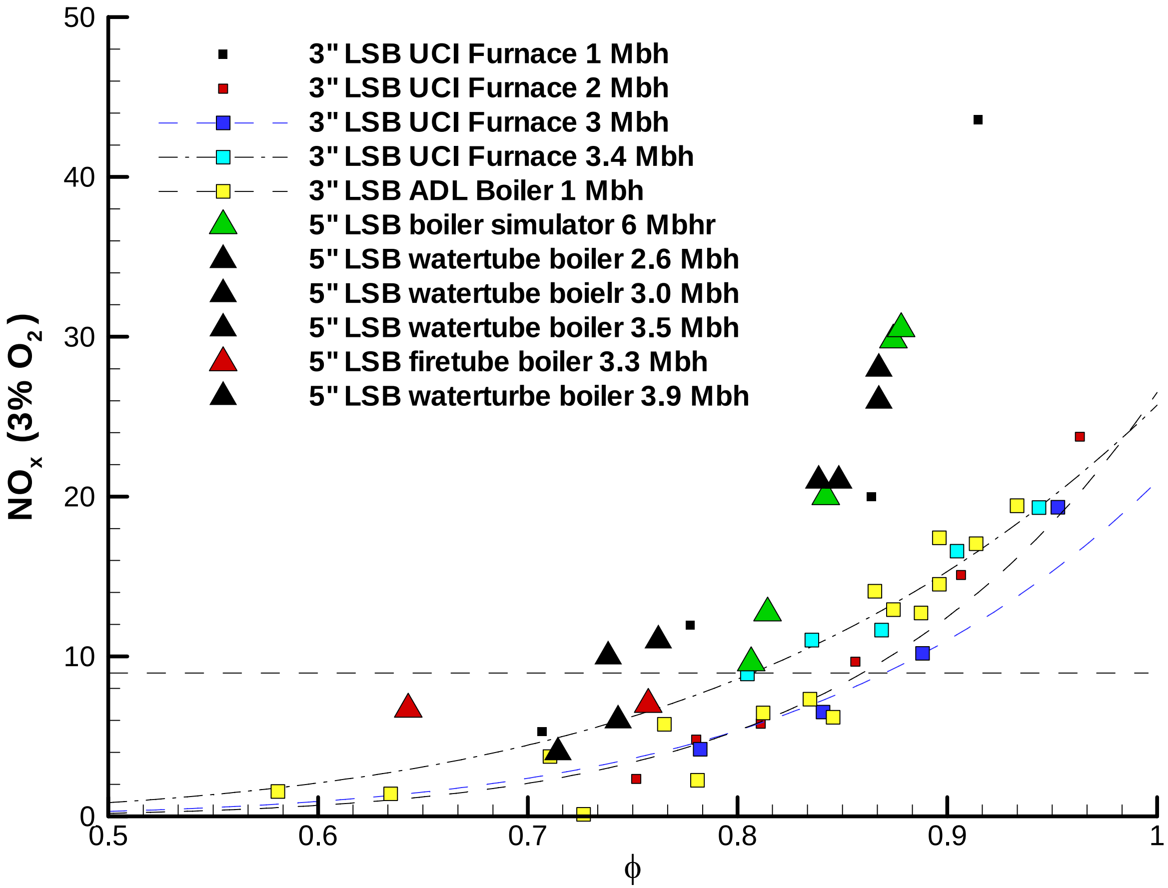
- New expression uses easily measurable parameters
  - **Ratio of center channel radius to burner radius, $R = R_c/R_b$**
  - **Straight or curved vane with angles, α**
  - **Ratio of mass flow rates through center channel and swirl annulus, *m***
    - **Standard pressure drop procedure to obtained *m* from different screens**

Developed Engineering Guidelines

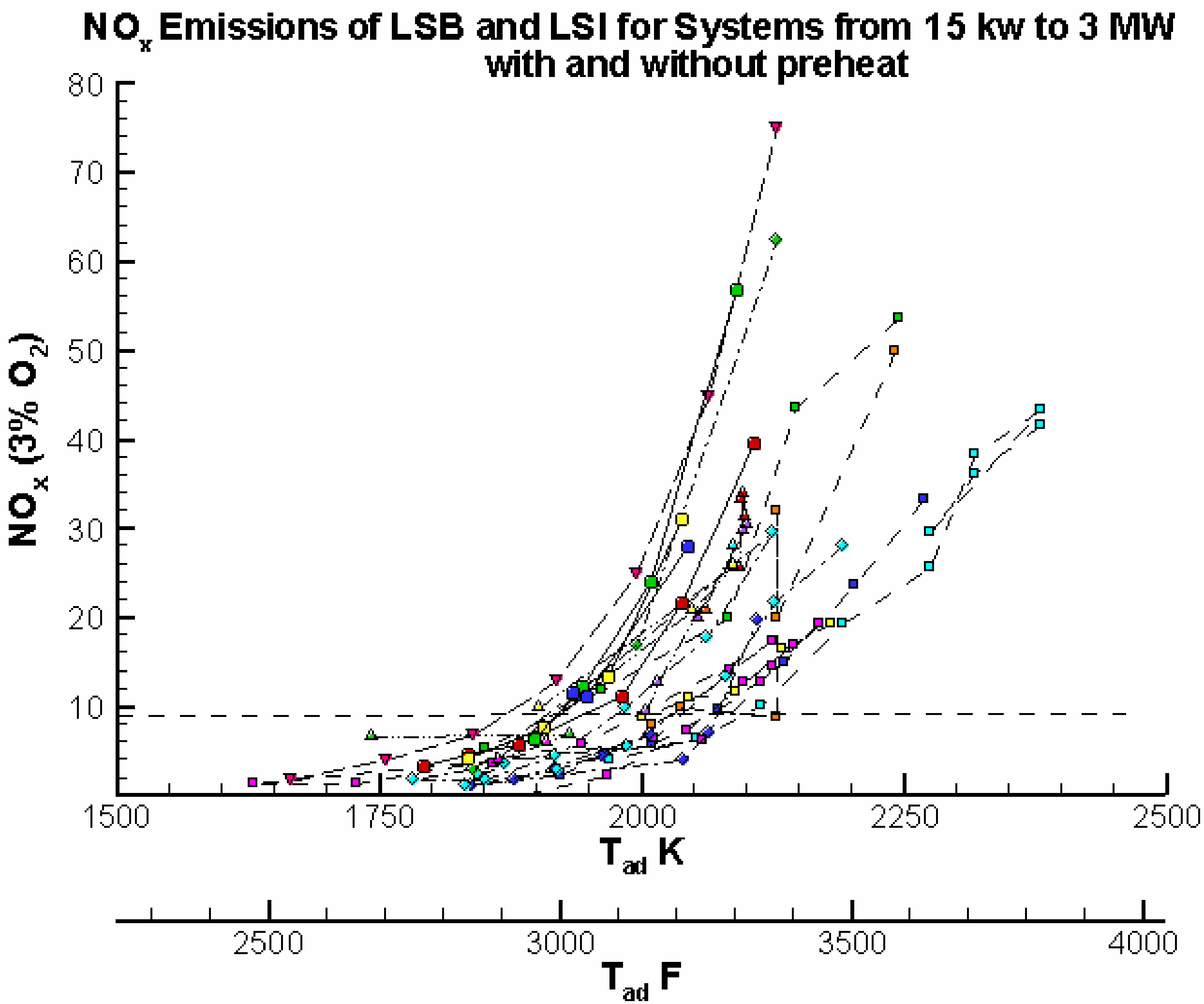
- Keep swirler recess at 1 to 1.5 diameter
- Apply $0.4 < S < 0.55$ criterion
  - Tune swirler by using different screens to change S
  - Screen geometry is not important
    - Use larger openings to reduce clogging problem
    - Can explore other options to balance core and annulus flow
  - Vane angle between 37^0 to 45^0
  - Vane can be curved or straight
- Constant velocity scaling applies
  - Minimum operating conditions predicted by the flash back point
- No need for elaborate and precise premixer

0.4 < S < 0.55 Criterion Scaled LSB to 40 cm and 13.5 MW

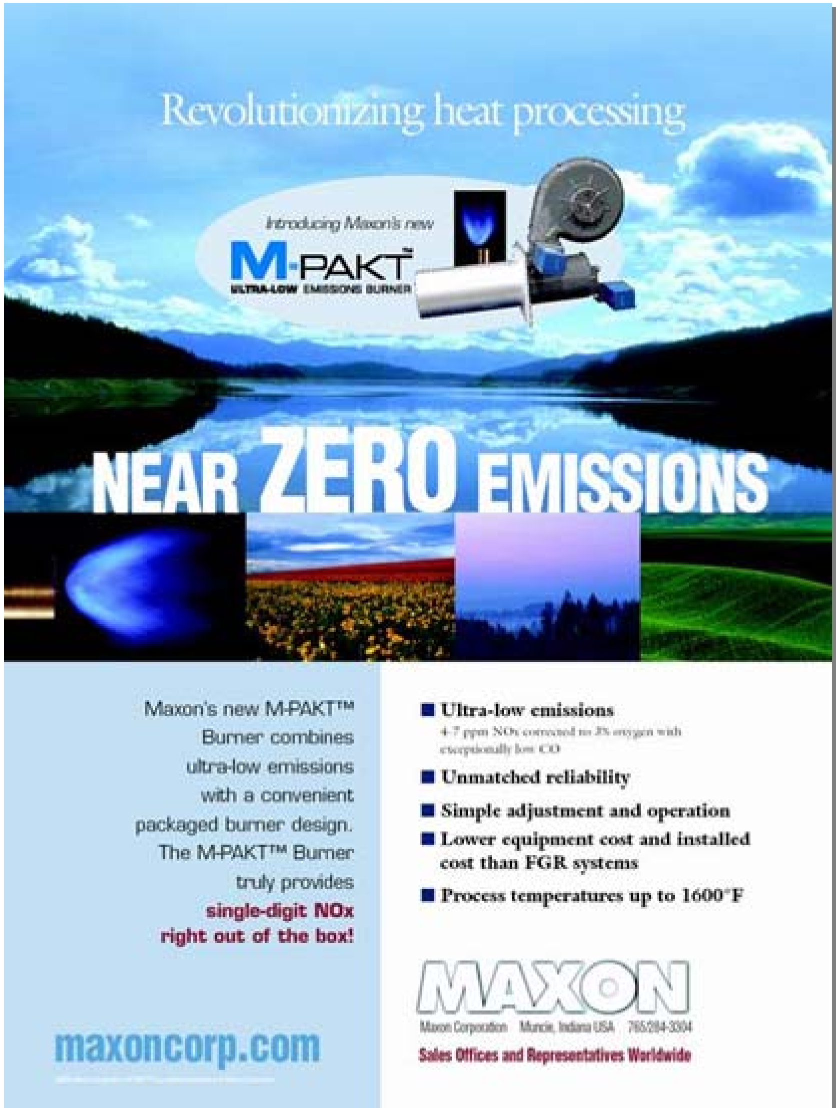
- Consistent NO_x < 9 ppm (3% O_2) in Industrial Systems



NO_x Dependence on Flame Temperature Shows Load Following Capability



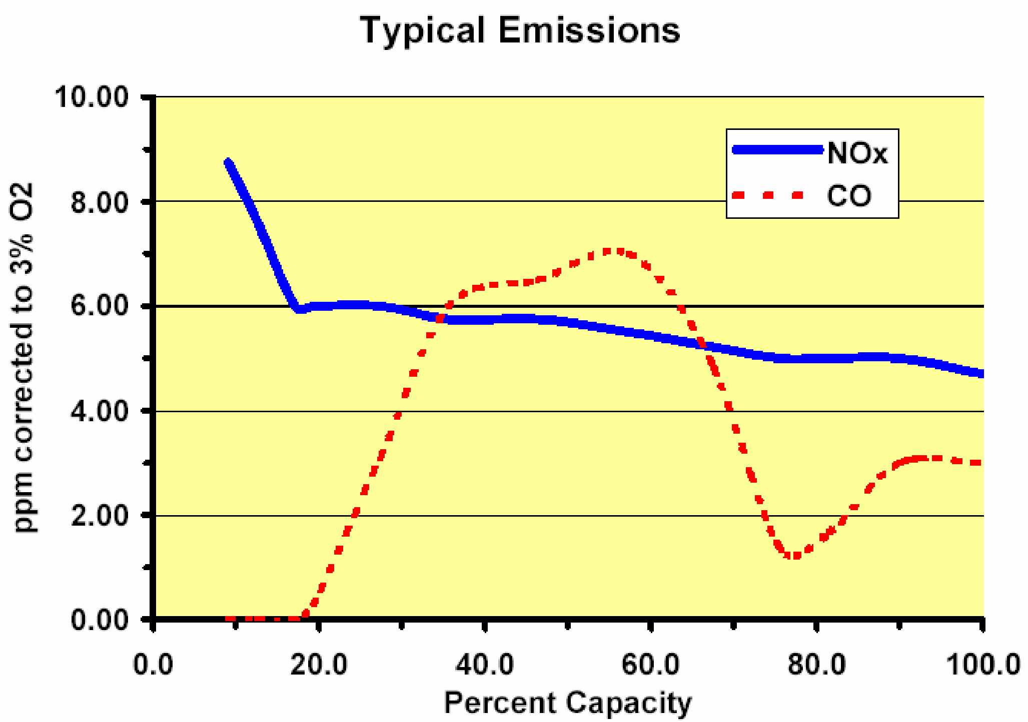
Commercialization for Process Heat



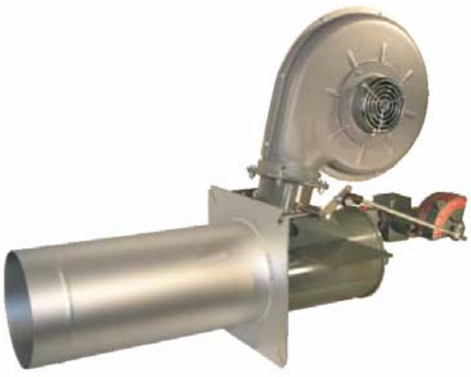
- Maxon Corporation licensed LSB in 2002 after a successful joint development and testing program with LBNL
- Target ultra-low NO_x market (< 9 ppm at 3% O_2 guaranteed) for industrial heating, baking and drying
- 300 kW to 1.8 MW (1 – 6 MMBtu/hr) products in production
- Tested LSB at 45 MMbtu/hr

M-PAKT Burner Maintains Ultra-Low Emission Throughout Load Range

M-PAKT™ Ultra Low NOx Burner



- Simple and compact premixer
- Conventional controls



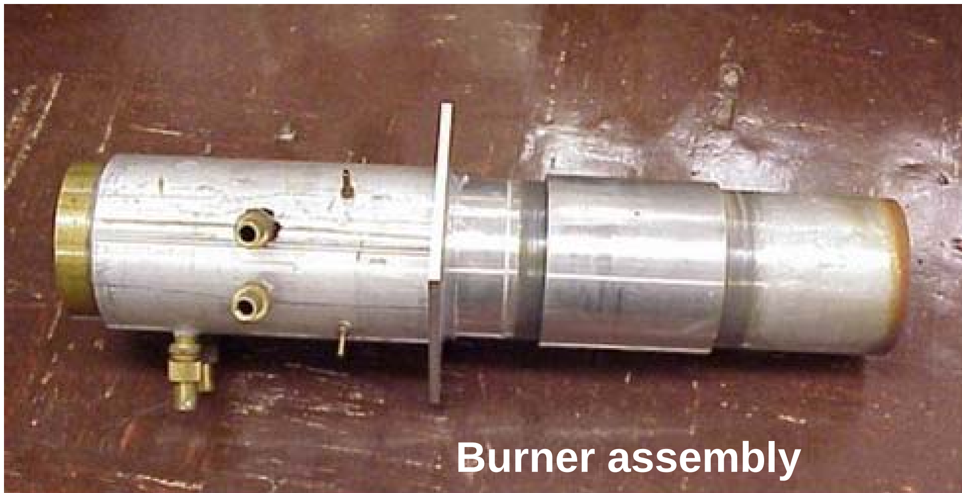
Maxon Identified Significant Economic and Technical Advantages of LSB

- ***Design scales by governing equations***
  - A radical departure from experimentation approach
- ***Size compatible to existing equipment***
- ***Fabricated with no initial re-tooling or new patterns***
  - Fewer parts from common materials
- ***Use existing controls for conventional burners***
- ***Flame not in contact with burner tip***
  - No thermal stresses to burner that causes metal fatigue
- ***Lower operational cost, and greater ease of operation, thanks to simpler combustion process***

Addressing Energy Efficiency Issues and Further Lowering Emissions

- ***Flue gas recirculation (demonstrated)***
  - Tested in boiler with external FGR
  - TIAX developed and tested internal FGR/premixer
- ***Reduce power of fan blower (accomplished)***
  - At least 50% reduction with no change in LSB performance
- ***Partial reforming to reach < 2 ppm NO_x (demonstrated)***
  - Traces of H_2 enhance flame stability and lower CO
    - Steam reformer or MIT's plasmatron
- ***Highly preheated combustion (demonstrated)***
  - Waste heat recovery
- ***Staging and burner/chamber coupling (planned)***

5” (12.7 cm) LSB for Boiler Testing


Burner assembly


Gas injectors


Flame lift-off height adjusted for boiler enclosure

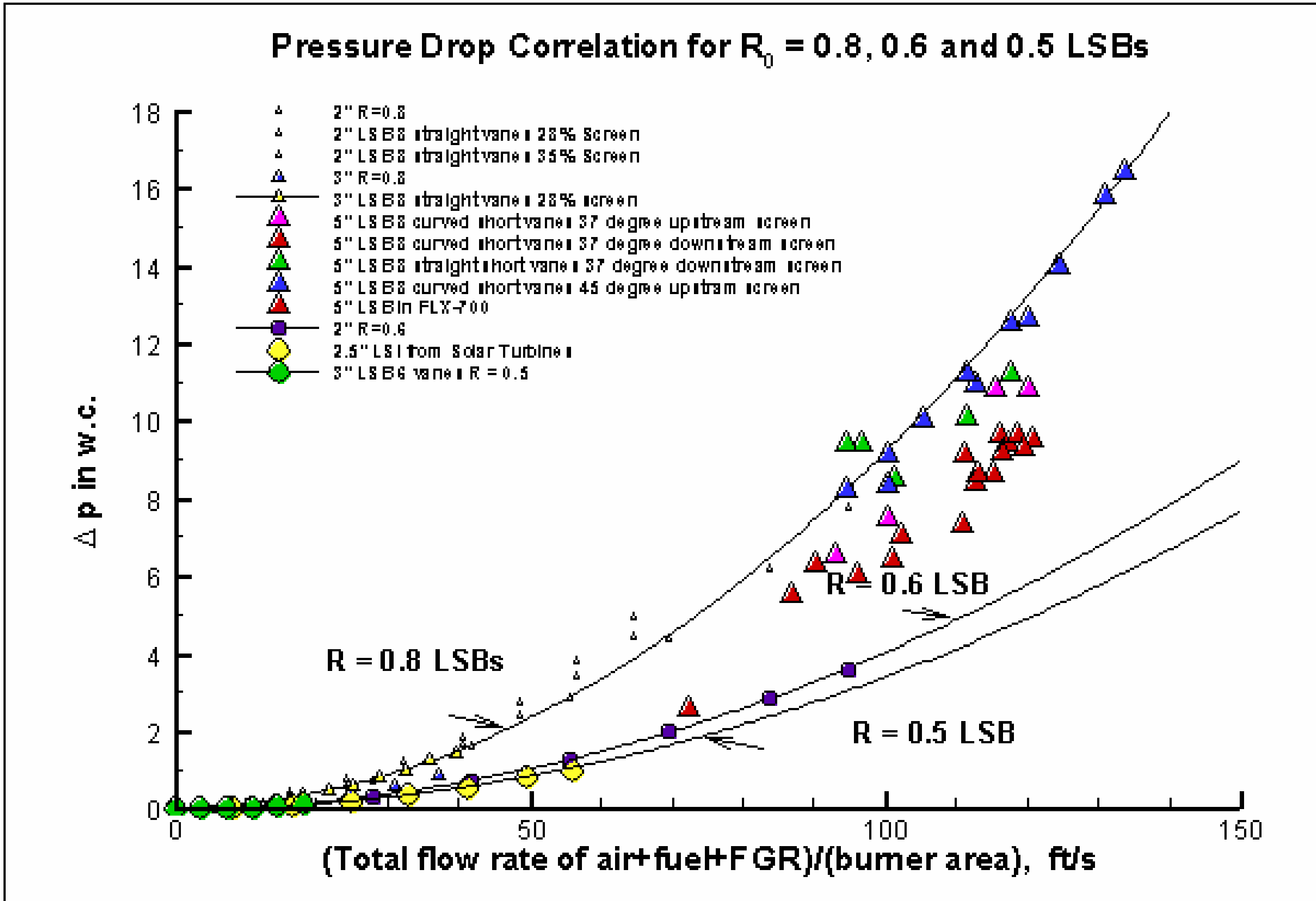
- Two 5” LSB prototypes
  - 0.5 – 7 MMBtu/hr capacity
  - R = 0.8 with 8 vanes
  - R = 0.6 with 6 vanes
- **10” LSB for up to 30 MMBtu/hr available in 02/2004**

Evaluate 12.7 cm LSB in Commercial Watertube Boiler with External FGR

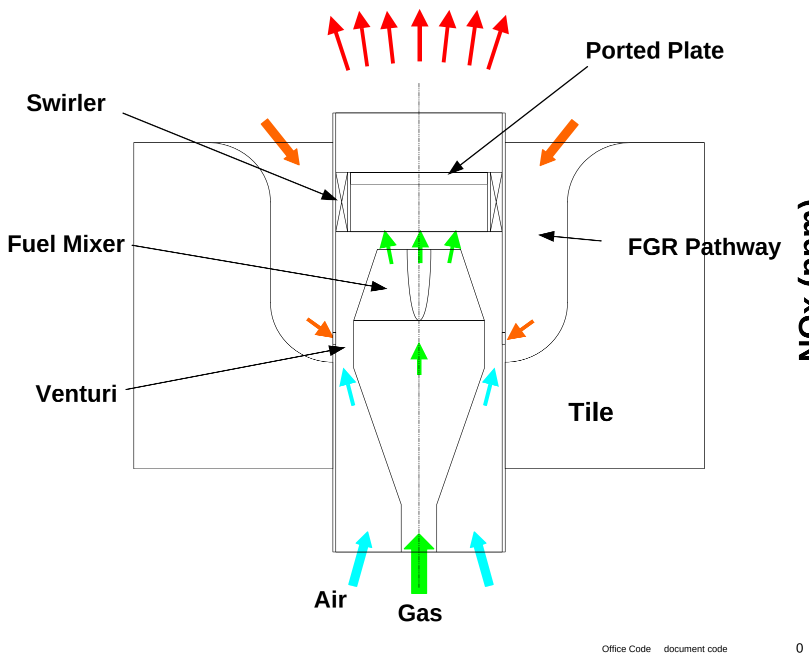
- Use blower and controls for the Cleaver-Brooks Boiler
- Performance targets
  - **CO < 12 ppm and NO_x < 9 ppm**
  - **.15 to 2 MW, 5:1 turn-down**
  - **ϕ > 0.87, < 35% FGR**
- LSB exceeded most targets
  - **< 9 ppm NO_x with < 12% FGR at ϕ = 0.87 at 1.2 MW**
- Fan pressure requirement slightly high

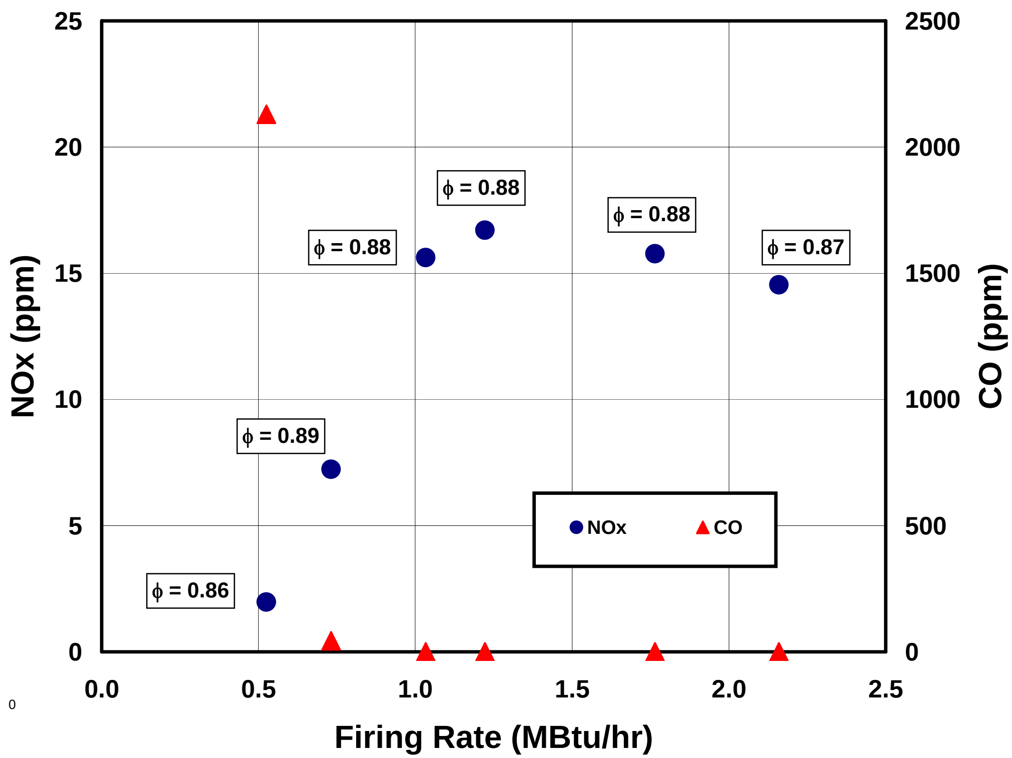
Smaller *R* Reduces Back Pressure

- Obtained equation for sizing fan requirement



ADLittle Developed and Tested Venturi Premixer and FGR Entrainer for LSB



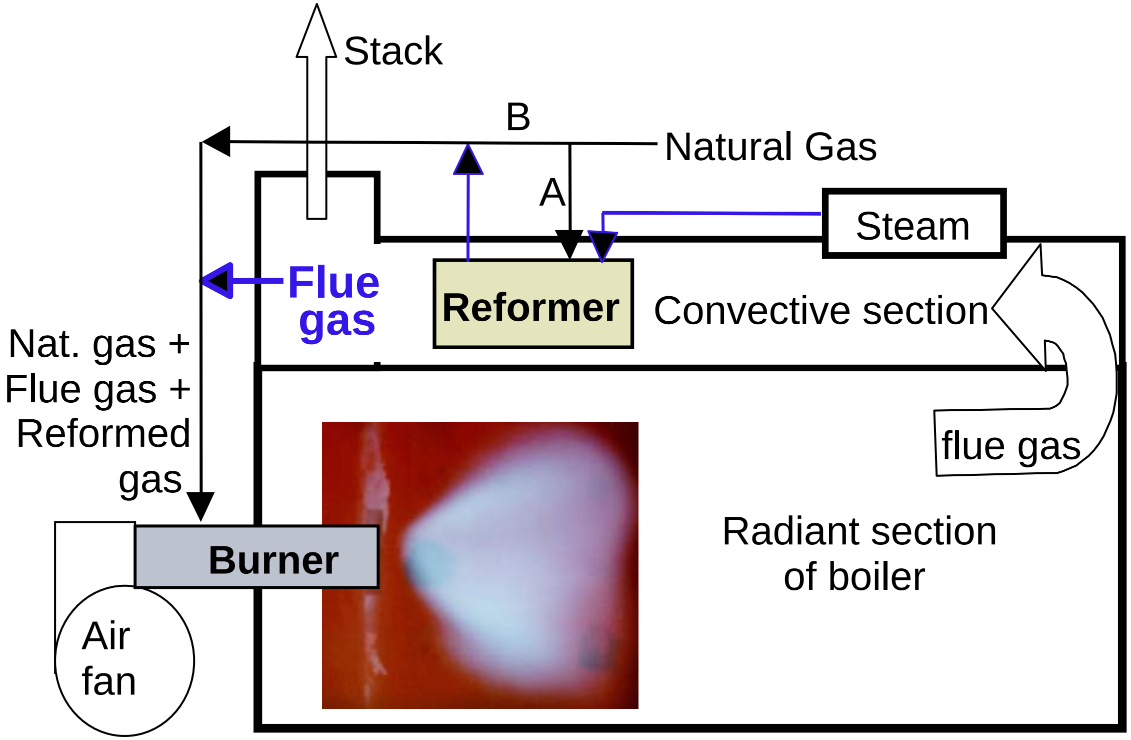


- Computation fluid dynamics (CFD) to optimize design
- Applied scaling equation to size LSB at 19 cm

< 5 ppm NO_x Concept -- FGR + LSB + Partially Reformed Natural Gas

- Exploit combustion of hydrogen enriched natural gas
  - Use LSB to capture these benefits
  - Partial reformer to produce optimum $H_2:CH_4$ ratio in fuel

- Demonstrated in 15 kW water heater simulator
  - $0.7 < \phi < 0.9$
    $0 < FGR < 0.3$
    PRNG = 0 and 0.05
  - Reformer at 650 C
    $CH_4 = 0.12$ l/s
    steam = 0.04 l/s
  - Steam (≈5%) has no effect on LSB



Current Status of LSB Development

- Formal and informal partnership with more than seven companies
- Prototypes from 8 kW (2.5 cm i.d.) to 10 MW (30 cm i.d.) all with ultra-low NO_x capability
- Demonstrated 60:1 turndown
- Demonstrated multi-fuel capability (pure hydrogen and other fuel blends)
- Tested for process heating, domestic water heater, pool heater, small boilers, and refinery gas boilers
- DOE-OIT funding to collaborate with boiler and burner OEM's
- Licenses available for boiler applications

Transferring Low-Swirl Combustion to Gas Turbines

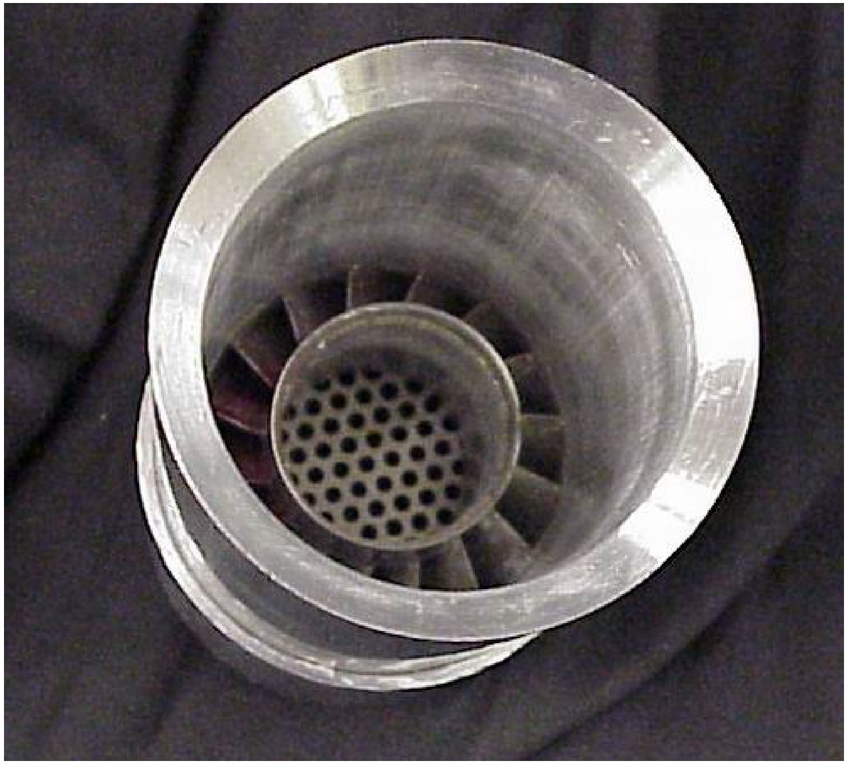
- Stationary land turbines are first to adapt lean premixed combustion to reduce NO_x
  - Dry Low NO_x (DLN) technology eliminates the need for steam injection
  - Current products guarantee < 25 ppm NO_x(@ 15% O_2)
- New air-quality regulations in California and many parts of US require < 5 ppm NO_x (@15% O_2) by 2005
  - DOE supporting research projects on catalytic combustors and surface stabilized combustors
    - Expensive materials that may degrade overtime
    - Elaborate controls needed to maintain smooth operation

Current DLN Gas Turbine Engines Use High-Swirl Injectors

- Center bluff body promote formation of recirculation
- Flame attachment at centerbody rim

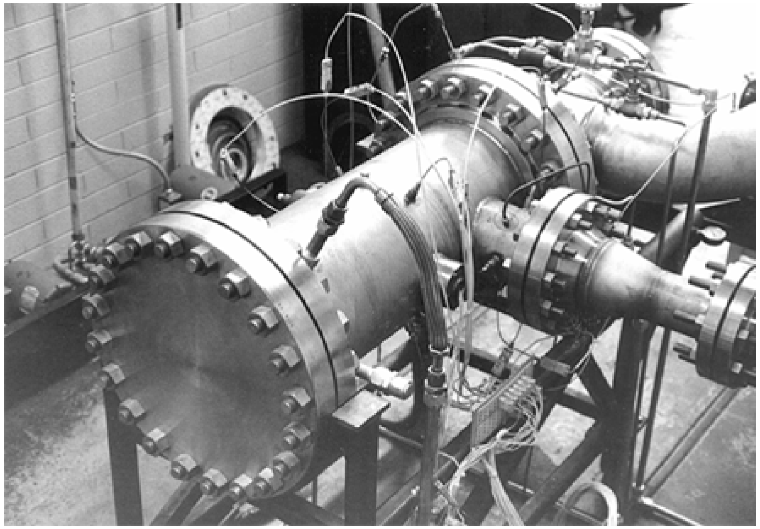
Low-Swirl Injectors (LSI) Configured in the Laboratory

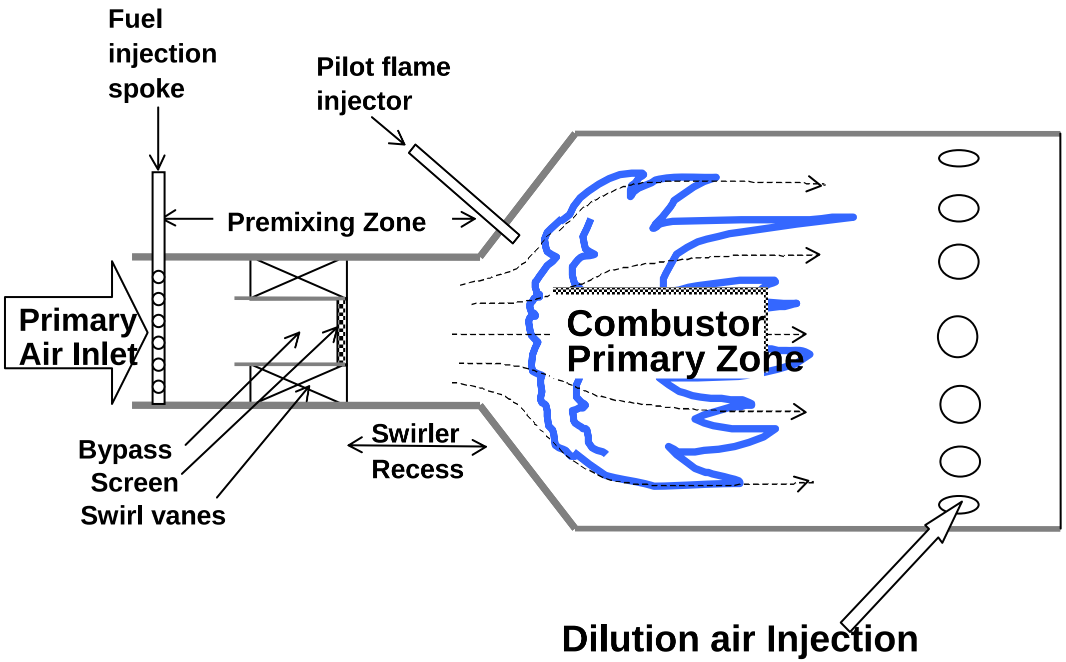
- Removed centerbody from SoLoNOx swirler
- Fitted with an exit tube (using 1.5 D rule)
- Vary center channel screen to optimize flame lift off height at 6-8 m/s



LSI Evaluated in a High Pressure Test Rig

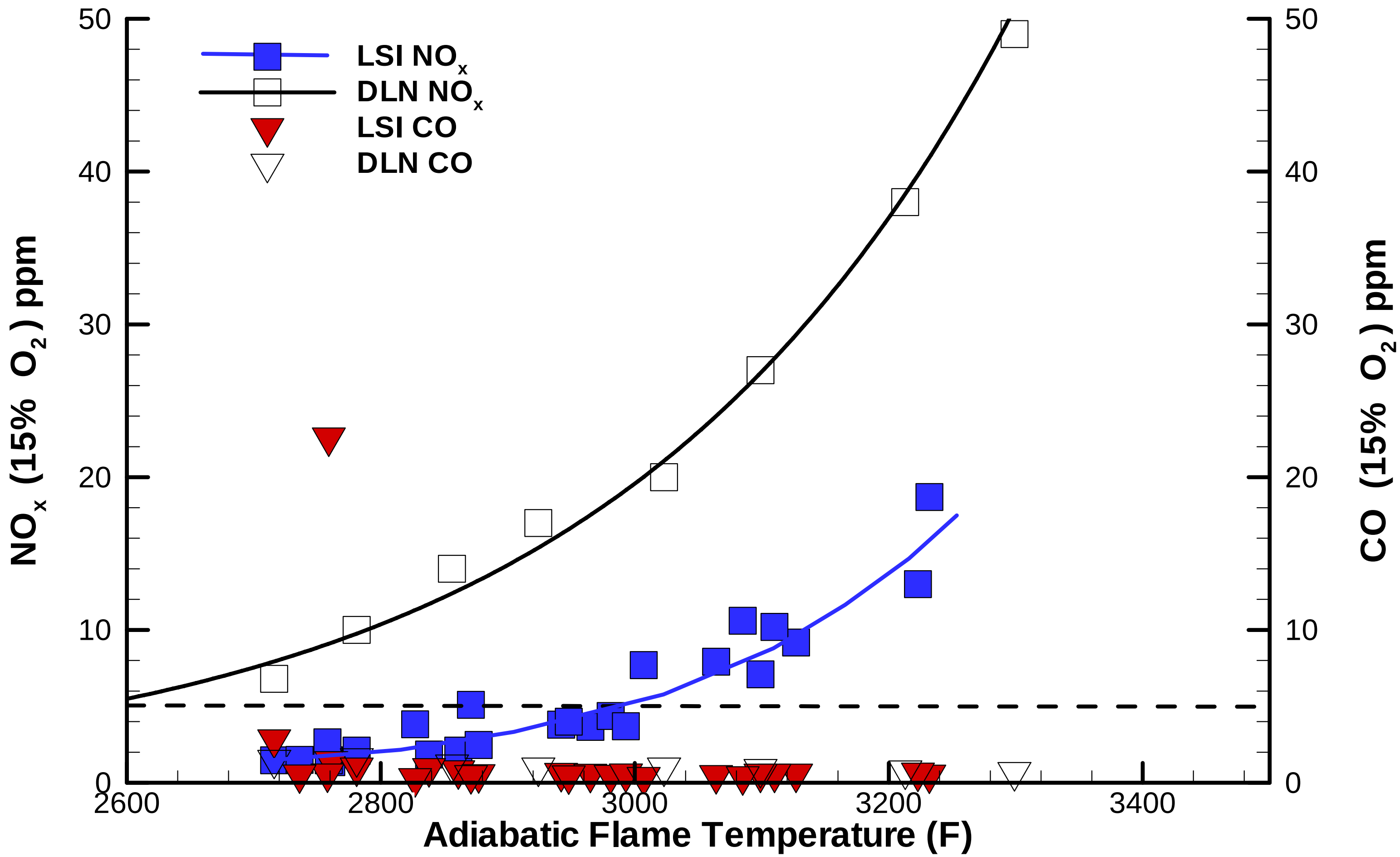
- Mounted LSI prototype in a Solar louvered combustor liner
- Tested at up to 600C preheat and at 15 atm
- Fuel introduced through fuel spokes or Solar’s advanced premixer



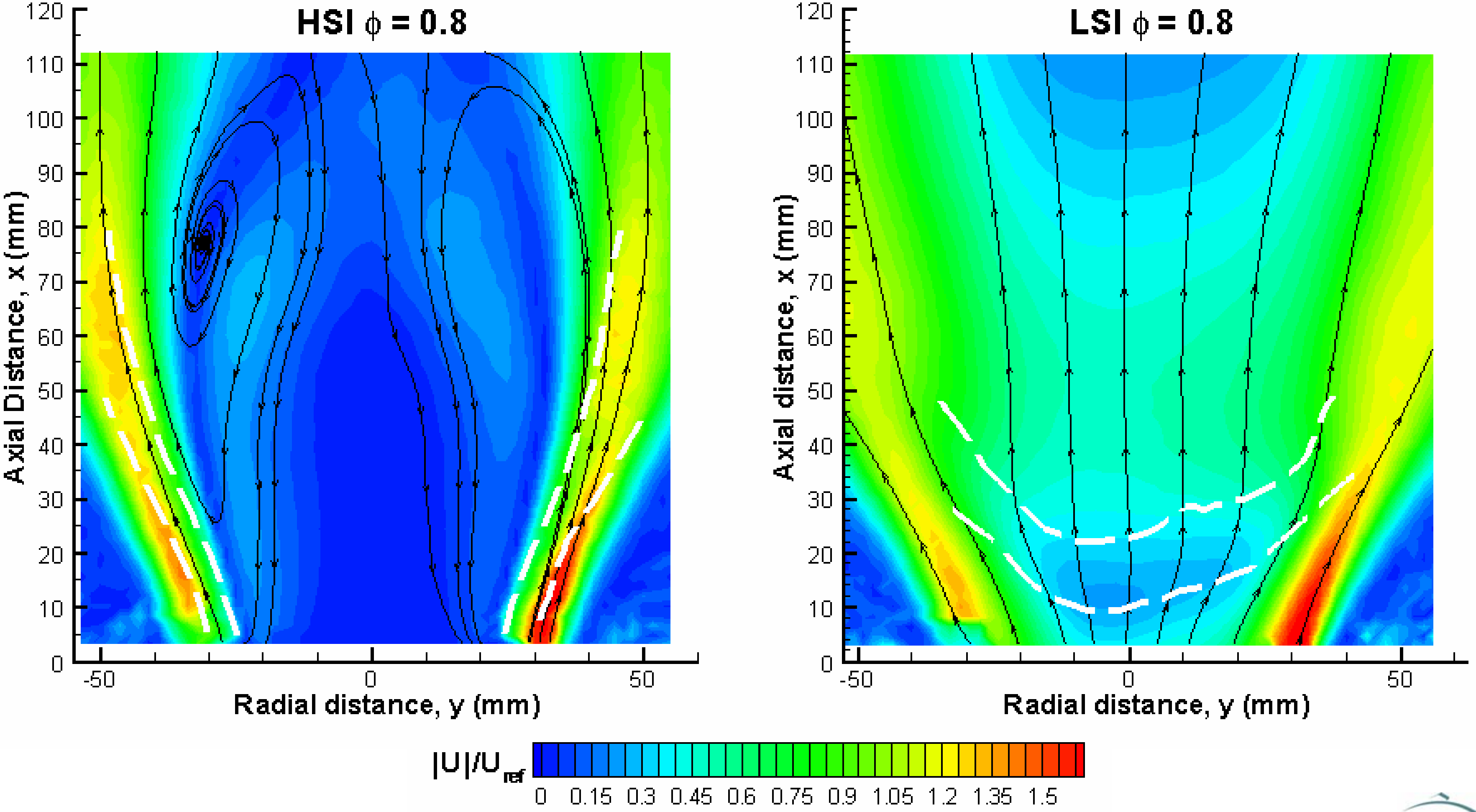


LSI Achieved < 5 ppm NO_x (15% O_2) at Full Engine Load Conditions

- Over 60% NO_x reduction compared to HSI with no compromise on performance



Absence of Large Recirculation in LSI Explains NO_x Reduction



Demonstrated LSI Concept for Mid-size Gas Turbine

- Fully compatible with existing engines
  - LSI prototypes made from SoLoNOx production hardware
  - very low add-on cost expected for implementation
- Lowest emissions matching those of catalytic combustors
  - No compromise on duty cycle time, and a much less elaborate and lower cost alternative
  - NO_x < 5 ppm conditions far from LBO & oscillations
- Show good promise to maintain low emission under partial load
  - does not required staging to maintain low emissions under partial load

Fundamental Research Enriched by Technology Transfer

- Provides important insights
  - Strong correlation of NO_x emissions with flame temperature for systems from 7 kW to 3MW
  - High combustion efficiency despite intense turbulence
- Identifies research needs
  - Turbulent displacement flame speed at high velocities
  - Flame properties at high inlet temperatures and pressures
- Indicates knowledge gaps
  - Fundamental properties of flames burning with multi-component and low heating value fuels
  - Burner/chamber coupling and post combustion chemistry and modeling

Planned RD&D Activities

- LSB
  - Process heat – develop enhancement methods with Maxon: staging, internal FGR and preheat
  - Boilers & petroleum refining – continue testing with potential development and commercialization partners
- LSI
  - Mid-size turbines – begin engine test in Winter 2004
  - Micro & utility turbines – seeking research & development partnerships and opportunities
- Enabling technologies
  - Partial reforming – seeking demonstration partners
  - Alternate fuels – demonstrated firing with H_2, HC/H_2, biomass & low-Btu fuels. Seeking R&D opportunities
  - Prevaporized premixed liquid fuels – initiated research at Nat'l Aerospace Lab. of Japan and discussion with U of Wash.
  - Combine heat & power generation – LSB+LSI: seeking R&D opportunities

Contact Information

- Robert K. Cheng
  - Senior Scientist
MS 70-108B, 1 Cyclotron Road
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
Voice: 510 486-5438, e-mail: RKCheng@lbl.gov
- Viviana I. Wolinksky
  - Licensing Manager
MS 90R1070, 1 Cyclotron Road
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
Voice: 510 486 6463, e-mail: VIWolinsky@lbl.gov